THE DESIGN OF MOOD CHANGING CLOTHING BASED ON FIBRE OPTICS AND PHOTOVOLTAIC TECHNOLOGIES

A thesis submitted by

Danying Yang

In accordance with the requirements for the degree of

Doctor of Philosophy

Heriot-Watt University

School of Textiles and Design

Scottish Borders Campus

Galashiels

April 2012

ABSTRACT

In the era of interdisciplinary research, smart clothes and wearable technology is at the forefront of innovation. High-tech and multi-functional smart textiles, of various types and constructions, challenge the design of clothes. Unconventional materials/fabrics have been investigated for highly fashionable clothing, and developed a flexible smart clothing system. A collection of high fashion clothes has been designed and made up with a number of SMART characteristics, forming part of a wider collection. The synergism between design and technology is underpinned throughout the project.

Electric power is provided by an array of flexible photovoltaic strips which have been carefully investigated so that they are functional but at the same time form part of the aesthetic design of the clothing. These PV strips are connected with conductive fabric and their energy is collected via a miniaturized electric circuit to store in a rechargeable Lithium battery. The purpose of this energy harvesting capability is twofold; one to charge personal mobile devices such as mobile phones and PDAs, and another to provide energy to an undergarment which is made of a woven luminescent fabric capable of changing colour by a stimulus from detecting the mood of the wearer. This mood changing function is provided by another miniaturised circuit with an audio sensor incorporated in it. The sensor picks up voice data and by analyzing its characteristics, it determines via a logic program in the circuitry the mood of the wearer (stress or relaxed) and it changes the colour of the garment accordingly via LEDs strategically positioned so that they provide the appropriate colour to the garment. The garment is woven with optical fibres and carefully incorporated in the design of the smart clothing system. The entire system has been designed, developed and implemented in a lady's and a man's fashion garments.

ACKNOWLEDGEMENT

I owe the deepest gratitude to my supervisor Professor George Stylios for his intellect, inspiration, enthusiasm and encouragement all through the body of this research work. His special vision of marrying Art and Science is much obliged. Thanks also due to the co-supervision of Ms. Theresa Coburn for her invaluable guidance and support in the design aspect of this research.

I acknowledge the sincere and professional contribution of Mr. Jin Zhou, Electrical and Information Department, Wuhan Polytechnic University, for the PCB related design part of this work.

Throughout the duration of the research, I would like to also thank members of Heriot-Watt University, particularly Mr. Peter Sandison, Ms. Fiona Waldron, Ms. Sandra Darling, Mr. Colin Turnbull and Mr. Liang Luo for their encouragement and kind advice. The friendly help of my colleagues and other fellow research students at RIFleX in the School of Textiles and Design will be unforgettable. A special and warm thank is given to Mohammad Issam Yousef for his valued assistance in video editing.

To my beloved parents, sister and husband, I am forever indebted to their immense care and endless love.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PRESENTATIONS AND PUBLICATIONS

1. "Mood Changing Garments", ATINER, 1st Annual International Conference on Visual and Performing Arts, Athens 2010

2. "The Concept of Mood Changing Garments Made From Luminescent Woven Fabrics and Flexible Photovoltaics", 4th International Conference "SMART Materials, Structures and Systems", CIMTEX 2012, Italy 2012

3. "Wearable Information Garment System For Health Monitoring", 12th World Textile Conference AUTEX, Zadar, Croatia 2012

4. "Wearable Mood Changing Technology", Knowledge Transfer Network, Materials Seminar, Edinburgh 2010

<u>In preparation for journals</u>

1. A wearable garment system for harvesting solar energy

2. A Luminescent fabric system capable of changing colour by microprocessor control

3. Mood Changing Wearable Electronics

CHAPTER 1 – INTRODUCTION

Smart textiles are materials that one or more of their properties can significantly change in a controlled way by external stimuli such as heat, light, electrical currents or chemical reactions. Clothing has yet to take full advantage from the potential of smart technology. And from the integration of science and art point of view, the essential requirement is harmonization of multidisciplinarity instead of compromised collaboration. Consequently it is not only the functionality of the technology that needs to be considered, but also the aesthetics of the design.

Responding to the increased interest in functional fashion aesthetics, the research in this thesis aims at integrating aesthetics and functionality by optimising clothing design for developing the new concept of SMART mood changing. Stimulated by the wearer's moods, responsive colour changing properties have been designed and developed in the clothes by fibre optic, wearable electronics and photovoltaic technologies. Tailor-made technological and aesthetic requirements of electronics, fabrics, clothing and hybrid combinations of materials and structures to connect unobtrusively have being researched and developed. A systems approach is followed from the concept of design through to the implementation and integration of design with technology.

The concept of the work, an overview of the system and its interactions with the wearer and the environment, and the multidisciplinarity of art with science through the harmonization of aesthetics and technology are stated in Chapter 2. Fashion and aesthetic garment design, smart technologies and their state of the art are also discussed. Chapter 3 deals with photovoltaic films, LEDs and fibre optic fabrics; it describes audio signal conversion technologies and investigates the technologies of mood changing based on harvesting solar energy. Fashion design research is carried out in Chapter 4 to use these technologies on a collection of two suits, one for a lady and another for a man which have gone through a complete designing, making up and integration process. The energy system and the information system of the clothing components are integrated in Chapter 5.

The actual implementation of the various parts is described in Chapter 6 with detailed illustrations. Fabricating, packaging and fitting have been considered in the design, and techniques have carefully been considered to fulfil the research requirements. In

Chapter 7, the newly designed clothing is presented, and experiments are being carried out with discussion of the results. The final conclusion and future prospects are stated in Chapter 8, highlighting the development of every design and technology aspect of the SMART clothing system.

CHAPTER 2 – STATE OF THE ART

The definition of "smart" is synonymous with intelligence and fashion. *Intelligent* implies the capacity to the intellect of knowledge and information, the ability to cope with demands arising from novel situations and to use the power of reasoning and inference. It may refer to having data storage and processing capabilities as in computer science. And *fashionable* suggests style or elegance in a dress or appearance, which is characterised by the influence of current popular trends or styles called fashion. The objective of design/technology based research is to explore the scientific side as well as the artistic side at the same time. In this way, a new breed of smart clothing is presented.

According to the description, *Smart Environment (SmE)* is a "physical word that is richly and invisibly interwoven with sensors, actuators, displays, and computational elements, embedded seamlessly in the everyday objects of our lives, and connected through a continuous network" [1]. *Ambient Intelligence (AmI)* refers to electronic environments that are sensitive and responsive to the presence of people. The term was coined in 1998 by Eli Zelkha and Brian Epstein of Paolo Alto Ventures [2]. *Smart Aesthetics (SmA)* refers to an interactive media which is responsive to a human change of mood [3]. Smart Environments, Ambient Intelligence and Smart Aesthetics are growing fast as multidisciplinary fields with a huge potential for benefiting humans and society.

Before analysing the project aims, a state of the art discussion in the areas of smart ambience and smart aesthetics indicates the implications of the advances in these fields of aesthetics and technology. And how by marrying both interesting new ideas can be successfully deployed.

2.1 Aesthetics

Aesthetics is an ancient Greek word meaning sensual perception of something that is nice [4]. During the Eighteenth Century, "aesthetic" was philosophically defined, and came to be used to indicate a kind of object, a kind of judgement, and a kind of value. Why and how do we judge beauty or ugliness, niceness or nastiness? In order to understand nature, it is not surprising that thinkers and philosophers have been probed into the essence of judgements about aesthetics over centuries, since beauty and ugliness are both important parts of our lives. Thus, aesthetics comes to examining our response to an object or phenomenon. The notion of understanding aesthetics as "a judgment of taste in the conditions of subjectivity and universality" given to us by Immanuel Kant [5]. Frank Sibley also claims that aesthetics are distinguished in requiring "taste, sensitivity and perceptiveness". In contrast, non-aesthetics may be employed by anyone with normal "eyes, ears and intelligence" [6]. For example, aesthetic concepts describe objects as "balanced, powerful, dynamic, elegant or melancholic", whereas non aesthetic concepts are referred to as "square, red, noisy, curved or sad". This gives us the thoughts and experience to judge an object, by "common-sense" or by "particular aesthetics".

2.1.1 Aesthetics, art and design

In accordance with the principles of good taste and the appreciation of beauty, aesthetics is the philosophy that is particularly possessed in art. As a vehicle for expressing or communicating the emotions and ideas, art is taken as knowledge or as action by using skill and imagination in the creation of aesthetic objects or experiences [7] [8]. Artworks can be defined by purposes, created by limitless concepts and shared with others, as seen in creative art or fine art. However, skill is used to express the artist's creativity, and engage with the audience's aesthetic sensibilities.

When this skill is being used in a functional object, it is considered as design with art forms, hence called applied art. For instance, industrial design, graphic design, fashion design, architectural design, and so on. With a broad connotation, design generally refers to creating or formulating a systematic plan, for a particular purpose or effect and in an artistic or highly skilled manner. Although artistic demand is increasing to produce objects, much research on design work is being focused on objective and measurable aspects such as functionality, efficiency and technicality. Aesthetic facets to design have fallen behind because of their subjective and affective properties [9]. Therefore, one of the primary concerns of this project is the design for aesthetics in fashion clothing.

2.1.2 Fashion design and intelligent clothing

As an applied art, fashion design allows people to express themselves through clothing affecting the unconscious mind. To express their personality, designers use contour scales, harmonic colour, textured fabrics, cutting and making up techniques to explore the profoundness of wear. Referencing the past and predicting the future, a variety of technologies are being used and developed to create fashion. At the same time, aesthetically pleasing fashion is reconsidered in response to the interpretation of the changing *Zeitgeist* [10]. From haute couture to ready-to-wear, then to mass market, fashion design is influenced by cultural and social attitudes to satisfy aesthetics at different levels. New developments in traditional and modern fibres, and in innovative new fabrics, fashion designers have a large combination of materials to work with. As can be seen in the high tech fashion, technology is not only used in the way of making or producing fabrics and clothing, but also extended to the wearable computing and information technology areas.

Being close to the body, clothing enables the intimate interaction of the human with his/her environment. This interaction is necessary for computer intelligence to be used for context recognition or as an intuitive interface. The WearNET is the example of a sensor system attached to the body that can provide a wearable computer [11]. How these technologies are being constructed and integrated into clothing aesthetically is currently a challenge.

2.2 Technology

Dating before the 20th century, the term technology is referred to describing the study of art, skill and craft [12]. In this, technology refers to tools and machines that may be used to solve real-world problems. It's a far-reaching term as the American sociologist Read Bain defines, "technology includes all tools, machines, utensils, weapons, instruments, housing, clothing, communicating and transporting devices and the skills by which we produce and use them" [13]. In its broader meaning, technology is the state of humanity's knowledge of how to combine resources to produce desired products, solve problems or satisfy needs. A current example is the designing of wearable clothing by combining electronic and information technologies with advanced physiological and psychological technologies. Hence, "State-of-the-art technology" refers to new high technology available to humanity at any time.

2.2.1 Technology, science and engineering

Since technology is referred in many aspects of our life, a basic question of what is our natural world and universe has to be raised. Science is aimed at discovering general truths and laws of the phenomenal world through observation and experimentation [14].

In 1992, it has been defined by the National Research Council as "Science is a study of our natural world and universe".

In comparison, William E. Dugger Jr. in 1993 defines "Technology is a study of our human created and controlled world and universe" [15]. Consequently, we can say that technology is the application of both science and the arts that forms or changes culture. As a cultural activity, technology is always connected to science and engineering.

Engineering deals with designing and developing tools, machines, structures, systems and processes by applying knowledge and techniques from science with practical judgement [16]. At this point, engineering has the same problem solving methods as technology, and could be considered as a specific study of a broader discipline of technology.

Science is dependent upon technology to test, experiment, verify and apply its laws and theories. Likewise, technology relies on science for its research, principles and knowledge base. With a symbiotic relationship between science and technology, engineering and technology have remarkable similarities in solving practical problems [15]. For example, science might study the flow of electrons in electrical conductors, by using already-existing technology. Then, the newly-found scientific knowledge may be used by engineers to create new tools or machines, like semiconductors, computers and other advanced technology. Therefore interdisciplinarity of more specialities are often integrated to solve a problem or make a product.

2.2.2 Smart textiles and wearable technology

Concerned with processes that we use to modify, change or control the natural world, technologies have to satisfy requirements such as utility, usability and safety. From Palaeolithic Age to Modern Time, historic inventions gave us a clear mind of how technology has been used and developed, for instance, the evolution of clothing from protection to fashion; the creation from the light bulb to television, from the computer to internet, etc. Consequently, scientific advancement and technological development have led to a host of new innovations.

As clothing interfaces between body and environment, new and innovative fabrics gave rise to epoch-making changes in clothing and fashion. Moving ahead of basic protection, new fabrics now have “high performance” like wind-proofing, waterproofing, breathability, fire-retardancy, bullet-proofing, anti-bacterial, etc. Beyond these highly-technical and multi-functional textiles, new technologies enable textiles to sense stimuli from the environment and respond, for instance; the application of shape memory textiles in climate-regulating garments [17]. These smart textiles having intelligent and communicative functions are being used in future fashion.

Wearable technology is emerging in prominence nowadays as one of the most advanced fields of high-technology. Wearable technology or fashion electronics are clothing and accessories incorporating microminiaturized electronic and computing technologies in a typical multidisciplinary approach of design and technology underpinned by textiles.

2.3 The Interface between Aesthetics and Technology

It shouldn’t surprise us that someone may think of wearing computers or measuring emotions. Creativity is found not only in arts, but also in science. Modern science is a discovery as well as an invention [18].

2.3.1 Divisions between art and science

Pursuing aesthetics and developing technology are perceived as two separate activities. For instance, an artistic designer may have no skill or knowledge of how to use technology; the scientist, on the other hand, does not understand why and how people judge beauty. The basis of the division between aesthetics and technology is because art designers are driven by aesthetics, senses and trends, whereas scientists are driven by functionality, efficiency and invention [19]. These divisions are now being bridged and this project is an example of such effort.

2.3.2 Harmonization of aesthetics and technology

The two domains need to be brought together, to bridge the division between aesthetics and technology because whenever technology signifies change, fashion realizes this change, and vice versa. When high-tech meets high-fashion, every design ought to incorporate practical functions and features as well as having a fine and fashionable look.

Fashion plays a crucial role in multi-functionality using high-technologies to reflect environmental issues from physical and psychological information. Many fashion/haute-couture designers use new technologies to probe new realms and to expand traditional boundaries of textile and fashion disciplines [20]. Encompassing high art performance and textile/material innovations, Hussein Chalayan established a dialogue between the wearer and the environment by using high-tech materials and systems, as well as collaborating with other textile and product designers. Figures 2.1 – 2.3 below show some of his intriguing collections.

Figure 2.1 Hussein Chalayan in collaboration with the London-based engineering and concept-creation firm 2D3D, Mechanically transforming dresses, Spring/Summer 2007 collection (Courtesy of Hussein Chalayan)

Figure 2.2 Hussein Chalayan in collaboration with Moritz Waldemeyer, The LED dress, Autumn/Winter 2007 collection (Courtesy of Hussein Chalayan)

Figure 2.3 Hussein Chalayan in collaboration with Swarovski, The laser and crystal dress, Spring/Summer 2008 collection (Courtesy of Hussein Chalayan)

In the field of intelligent clothing, more complex innovations and high technology play a crucial role. An emerging number of companies are now showing great interest in collaborative research projects with electronic engineers/programmers and textile/fashion designers [21]. Philips-Levi's® is a company that used hi-tech in their Industrial Clothing Division Plus range (ICD+) launched successfully in the year 2000. As shown in Figures 2.4, this range is comprised of wiring wearable electronics in water-resistant outerwear jackets which can provide remotely controlled communication with a mobile phone, an MP3, etc. There are others like Infineon, CuteCircuit, Samsonite, Adidas and Nike, developing intelligent wearable products for sports, medical and military uses.

Figure 2.4 Philips-Levi's® ICD+™, Smart jacket equipped with the mobile phone and MP3 with remote controlling, Spring/Summer 2001 (Courtesy of Philips-Levi's®)

2.3.3 E-textiles as the interface between wearable technology and smart clothing

Presently, much research is being carried out using E-textiles, also known as electronic textiles, incorporating smart wearable technologies. These fabrics enable active communication via embedded digital components, miniature electronics and portable computers [22].

E-textiles become the key interface between wearable technology and smart clothing in two ways:

– Conventional E-textiles use classical electronic devices such as pure wires, integrated circuits, LEDs and conventional batteries into clothing;

– Advanced E-textiles, sometimes called fibertronics, use conducting and semi-conducting materials, or more advanced electronics such as transistors, diodes and solar cells [23].

Technically these novel functions require various specialities of textiles, electronics and telecommunications for smart clothing. For example, touch buttons are constructed from textiles by using conductive textile weaves and then connected to devices such as music players carried in the garment [24].

Smart clothing is a typical consequence of the collaboration of clothing design and electronic technology. Environment sustainability is another topic of huge importance after the emergence of smart technologies. Energy harvesting based on textiles and clothing is a new aspect of endeavour. Under the aim of well being, clothing and fashion markets are flourishing with a variety of smart clothing designs like solar-powered jackets such as SCOTTeVEST shown in 2004 (Figure 2.5), Ermenegildo Zegna presented in 2007 (Figure 2.6), etc.

Figure 2.5 Solar-powered jackets, Scottevest Inc., 2004 [25]

Figure 2.6 Solar-powered jackets, ZegnaSport, 2007 [26]

At the same time, light-emitting products have also been attached to clothing with innovative materials and textile design. For example, Figure 2.7 shows an electroluminescent raincoat glowing in the rain; and Figure 2.8 shows an LED light-emitting display on clothing.

Figure 2.7 "Puddlejumper" created by Elise Co, 2006 [27]

Figure 2.8 "Lumalive" photonic textiles designed by Philips®, 2006 [28]

As can be seen, many efforts have been made to promote extra active functions and intelligent properties of traditional clothing, such as the use of renewable energy sources for recharging mobile electronic systems, or the application of textile-based displays to illuminate motifs or transmit information. Nevertheless, solar energy may be integrated into the clothing as add-ons but poorly adapted to fashionable styles of the clothing, because of its large surface requirements related with its effectiveness; the same can also be said for the thick and rigid illumination displays shown by electroluminescent coating layers and wiring construction. These efforts are more intended to ensuring the working of the new functions instead of being truly infused into the design concept of clothing/fashion.

Unlike the restriction of membrane and coating technologies, optical fibres have played a prominent role in the mergence with textile structures. The Luminex company has produced garment tops made out of fibre optic woven fabrics that maybe permanently illuminated [29]. These efforts have shown more advantages in decorating static interior design, due to their limitation in dynamic clothing appearance and comfort when large electronics, battery packs and rigid wire connections need to be applied.

Another challenge is how could these functions and performances presented as smart "second skin" or intimate "communicative apparel" to human beings in terms of shaping, patterning and colourize any future fashion? In a truly smart or intelligent manner, textiles/clothing can sense, react even adapt to environmental stimuli [30]. Lately advances have been made to developing wearable technology and smart clothing further in physiological and psychological areas. For example, the Japanese company Neurowear is creating a range of fashion items for mind control applications. By picking up the brainwave signals and converting them into visible actions, these products can correspond to different brain activities, such as concentrating or relaxing, as seen in Figure 2.9.

Figure 2.9 "Necomimi", Brainwave-controlled cat ears for humans, created by Neurowear, Japan 2011 [31]

However these types of products may be seen as “gimmicks”; the pair of ears might be more suitable for fancy dressing instead of daily wear. Professor Stylios and Meixuan Chen are investigating the interaction of SMART designs with brainwaves in a quest to design psycho clothes [3].

2.4 Discussion, Conclusion and Project Aims

The challenge of how could technology to be applied on multi-functional clothing whilst at the same time increasing the clothing aesthetics is continuing. For achieving a smart system, aesthetics is pursued as a critical reflection of art, culture and nature, while technology is generated by the creation of science, knowledge and spirit. Therefore, the combination of Electronics/Computing/Information Technology and Clothing/Fashion/Couture Design through the Textile/Material medium provides multifunctional products with intelligent concepts for enriching human life by marrying Art with Science.

As technology is being applied to textiles and clothing, how radically will fashion change the way we dress in the future? Problems/shortcomings of previous work raise questions:

– Fashion and functionality are still someway apart from each other. Smart clothing technologies have been effectively engaged in military, medical and sports, to a larger extent by adding functionality and to a lesser extent by being totally responsive. But there are only a few clothes with emphasis in fashion or bespoke tailoring. Hi-tech fashion and couture seen on the catwalk are not made to be worn by the public or not being capable of washing, and are only limited to be displayed in galleries.

– Boundary crossing between many disciplines and particularly in design and technology is lacking common language and true collaboration. Designers stress passionately the importance of aesthetics, while scientists expect them to understand and grasp fast developing technology. To put the minds of designers and scientists together depends firstly on establishing a common communication platform and at the same time understanding of aesthetics, technology and the end user. Practically this gap needs to be bridged by educating and training them in both disciplines. It is a cultural difference that needs changing.

– A systems approach should be used in all design and technology developments, in place of fragmented add-ons of technology to conventional clothing. Good design and technology should be investigated at the early stages of conceiving the creation of the idea.

Bearing these aspects in mind, this work was undertaken as a concept of a system by integrating design and technology into a fashionable SMART clothing range. The implementation showpiece is based on how to design, develop and present highly aesthetic mood changing clothing by harvesting energy. To that effect, two representative designs have been presented: a lady's and a man's couture suits. These garments are presented live in the CD of Appendix C in this thesis.

More explicitly the aims of this project are as follows:

1. To integrate design with technology for the creation and development of a SMART clothing system without any compromise of its aesthetics.
2. The SMART clothing system should be based on mood changing principles and be responsive to a stimulus.
3. The system should use and harvest energy from the environment making it energy efficient.
4. Wearable electronics should blend well with the garment design and have unobtrusive connections with the textile fabric parts.
5. The SMART clothing system should form a suit capable of presentation as a fashion statement.

The thinking that has led to the above aims is further articulated in Chapter 4.

CHAPTER 3 – TECHNOLOGY STATEMENT

3.1 Energy Harvesting – Solar

Energy harvesting (or power harvesting/energy scavenging) has gained much interest in the last few years. From photon, thermal, vibration sources and the like, energy harvesters provide small power for low-energy consuming electronic systems. This is important for effectively utilizing energy sources and promoting new smart system development for everyday use. Our daily life is in ever greater need of energy, realising that this demand is not sustainable, so the quest of switching to other energy resources is at the forefront of current development, from energy accumulation to energy reservation, as shown in Figure 3.1.

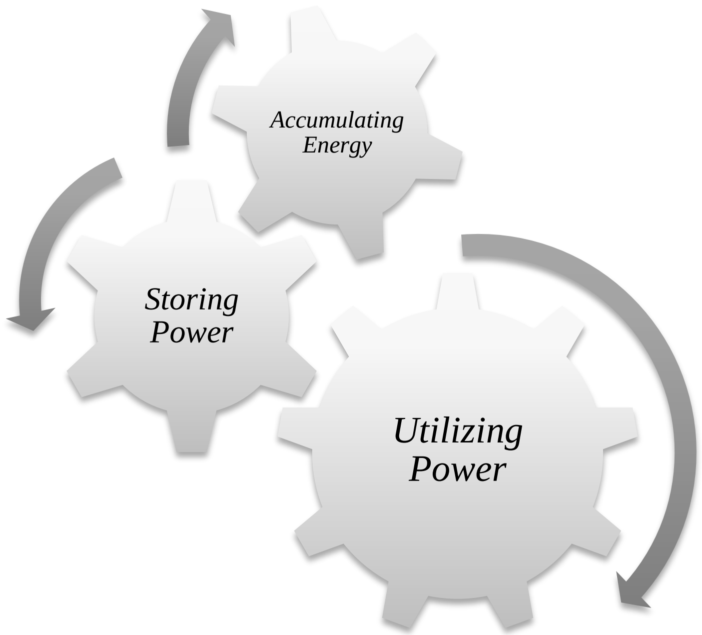


Figure 3.1 Energy harvesting system

– Accumulating energy

Solar energy is currently a primary energy source used by humans based on reflection and absorption by the sun in the atmosphere. Its potential of undergoing conversion to all forms of energy is enormous, renewable and sustainable [32]. Although we have seen such solar energy applied to architecture, solar application to smart wearable electronics on clothing is difficult and scarce. Typical power capacities from solar harvesting devices are highly dependent upon the specific application and the purpose of their use. To integrate solar into clothing, the material characteristic and fabrication technology are important for wearing and washing, on top of the fact that a smart clothing system would require low power and reliance on energy in a battery.

– Storing power

From a scientific and technical viewpoint, scavenging energy directly from ambient has still limits in terms of efficiency and continuous access. Energy storage becomes important supplement to variable or inefficient power supply with power management circuitry. Rechargeable batteries compatible with the output devices are therefore used to provide a steady flow of energy, along with carefully regulated low energy circuit design.

– Utilizing power

After the electrical power generated from solar energy is accumulated in batteries, controlled by carefully designed low energy circuitry, the power can be delivered to devices at will. The state-of-the-art of energy harvesting techniques, power conversion, power management and battery charging have given rise to low-power systems which have triggered series smart technologies [33]. Applications are not only for conventional portable electronic devices such as mobile phones, but can go beyond to wearable interactive control systems, as in the case of this project where the information is fed back to the wearer.

3.1.1 Photovoltaic (PV) energy harvesting

At the first stage of this research, photovoltaic technology is integrated to innovative clothing design. A solar harvesting process was considered by which energy is derived from sunlight, captured and stored in a battery, to then power and recharge a mobile phone, an MP3 or a PDA. This is the initial application of PV to wearable electronics in the context of this project. The second stage is the use of the energy to power the mood changing system as will be described later.

An understanding of PV principles, operation and use is needed before designing the system, such as the components and connection of a PV system, its working efficiency and conditions [34]. The grid-connected *photovoltaic system* is composed of photovoltaic cells to an array as illustrated in Figure 3.2. *Solar cell* (or photovoltaic cell) is an energy generator that converts the energy of light directly into electricity by a photovoltaic effect. Due to the low voltage of an individual solar cell (typically 0.5V), several cells are connected with each other in series to increase voltage in a weatherproof encapsulation assembly called a *photovoltaic module*, also known as *solar* *panel*. The power that one module can produce is usually not enough, several modules are interconnected therefore, in series or parallel, or combined, to form *photovoltaic arrays* according to end using requirements of DC voltage and current. [35] Although solar cell efficiencies are increasing along with new technological developments, the single cell efficiency is still low about 8% for thin films and 18% for single crystal silicon [36].

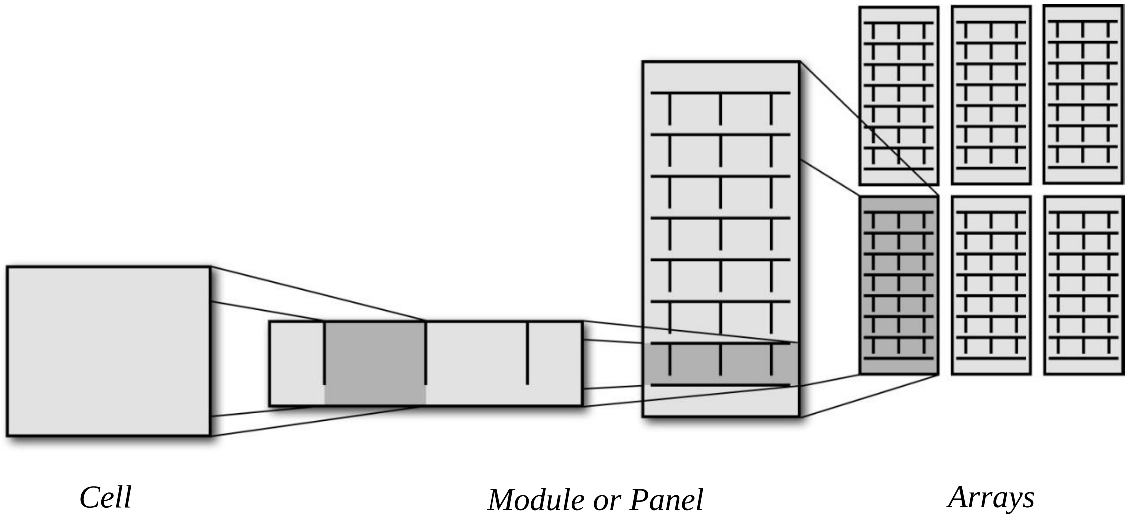


Figure 3.2 Photovoltaic (PV) system

The PV system in this research is devised from a single solar panel to a PV array for use after regulating or modifying the electrical output. For using the PV array to power or recharge portable devices on clothing, such as mobile phones, three key elements have been considered: module properties, panel mounting and array formation.

<u>Module Properties</u>

Silicon is a known well-researched material in both bulk and thin-film forms [37]. It is made by layers of photovoltaic depositions, flexible substrates and transparent coatings. Thin-film silicon is manufactured directly into modules. Opposed to wafer silicon, it presents an interesting alternative in the solar industry. For fabric applications and in clothing, thin-film photovoltaic modules are preferred due to their flexibility compared with bulk and rigid wafer panels.

PowerFilm series of photovoltaic thin film panels as seen in Figure 3.3 were chosen for this project because they have the advantages of simple roll-to-roll technology, flexibility, and are lightweight and practical. These flexible solar panels are practically capable of portable charging and suitable for different weather conditions [38]. In order to specifically develop the charging function for portable electronic devices on clothing, such as a mobile phone or an MP3, 3~4V flexible solar panels were chosen. The specifications of 3~4V range panels are shown in Table 3.1. The PV models (05-1287) have small dimensions but proportionally high voltage being one important criteria and thus chosen for this project.

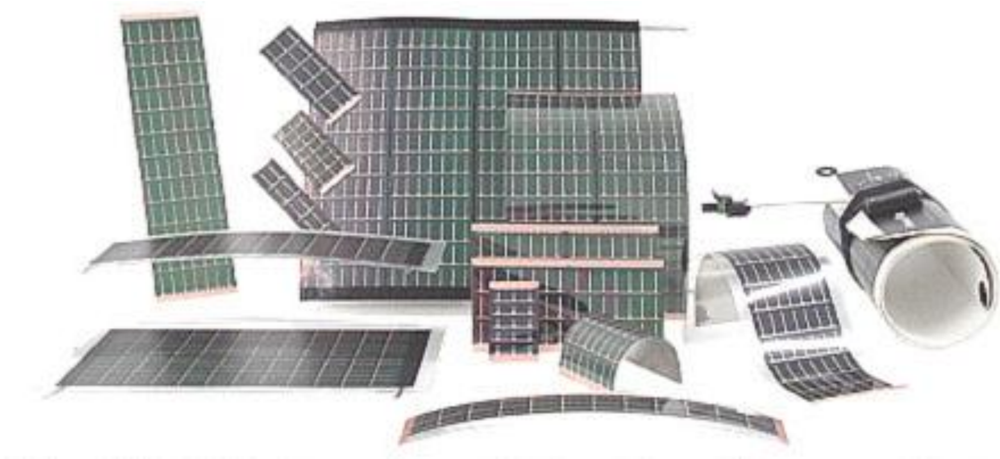


Figure 3.3 Flexible solar panels (Courtesy of Silicon Solar Inc.)

Model #	**Operating Voltage (V)**	**Operating Current (MA)**	**Size (L×W×T) (INCHES)**	**Weight (OUNCES)**
05-1282	3.0	22	2.5×1.5×0.01	0.03
05-1283	3.0	25	4.5×1.0×0.01	0.03
05-1284	3.0	60	4.5×1.5×0.01	0.04
05-1285	3.6	50	2.9×3.0×0.01	0.06
05-1286	3.6	100	2.9×5.9×0.01	0.10
05-1287	4.2	22	3.3×1.5×0.01	0.03
05-1288	4.8	50	3.7×3.0×0.01	0.07
05-1290C	4.8	100	3.7×5.9×0.01	0.10

Table 3.1 Specifications of PowerFilm series photovoltaic panels, 3~4V, the optimum PV model is highlighted

Panel Mounting

After choosing the optimum size of the solar panel, its electrical connection and protective package needed to be designed. Each panel has large silver/copper terminals which make it possible to connect multiple panels and develop a powerful PV array. Protecting the PV terminals from degradation by environmental exposure while minimizing the coverage of the cell surface for reducing optical losses, the design of the panel package is crucial. The need of joining different materials together when designing non-textile solar panels on textile-based clothing requires careful consideration. Considerable testing has been done to package the solar panel, by investigating traditional stitching method shown in Figure 3.4, and heat-sealing method in Figure 3.5. A new embedding method shown in Figure 3.6 has been devised which has the merits of stitching and heat-sealing. Conductive fabrics and snap fasteners are applied for connection instead of wire soldering. The combination of flexible film-like materials and weatherproof fabrics was successful in featuring functional as well as aesthetic attributes to the newly designed clothing system.

Testing 1: Traditional stitching method

— Knife-point needle of size 75/11 N/M;

— Needle-feed machine;

— 120's polyester core spun thread;

— Large stitch of 4mm.

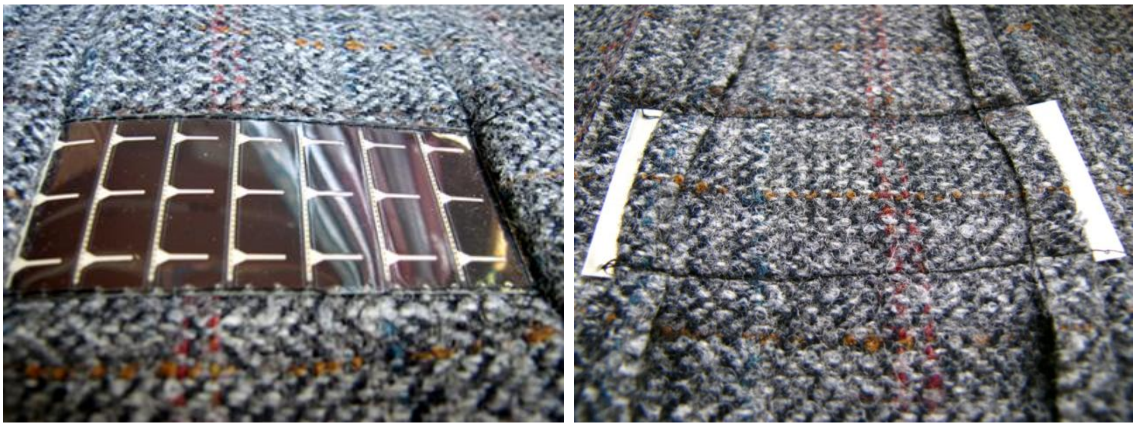


Figure 3.4 Solar panel's package by traditional stitching – Front and Rear

Testing 2: Heat-sealing method

— Temperature of 150~200°C;

— Heat-sealed edges for waterproof;

— Used for synthetic fibers made from thermoplastics, such as polyester or nylon.

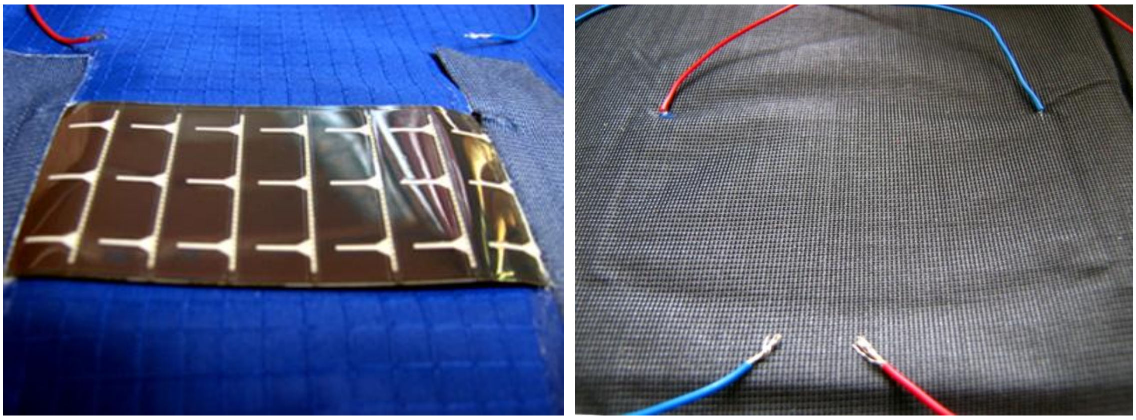


Figure 3.5 Solar panel's package by the heat-sealing method – Front and Rear

Testing 3: Embedding method – Heat-sealing and Stitching

The following operations have been carried out;

— Heat-sealing the rear side and edges of each PV panel by transparent PU thermoplastic adhesive tapes and Gore-Tex fabrics, at 150~200℃ temperature;

— Modular window mounting by Gore-Tex fabrics, of blind stitching and reinforcing top stitching;

— Extending the terminals by adhering conductive fabrics, fixing snap fasteners, and covering by waterproof fabrics.

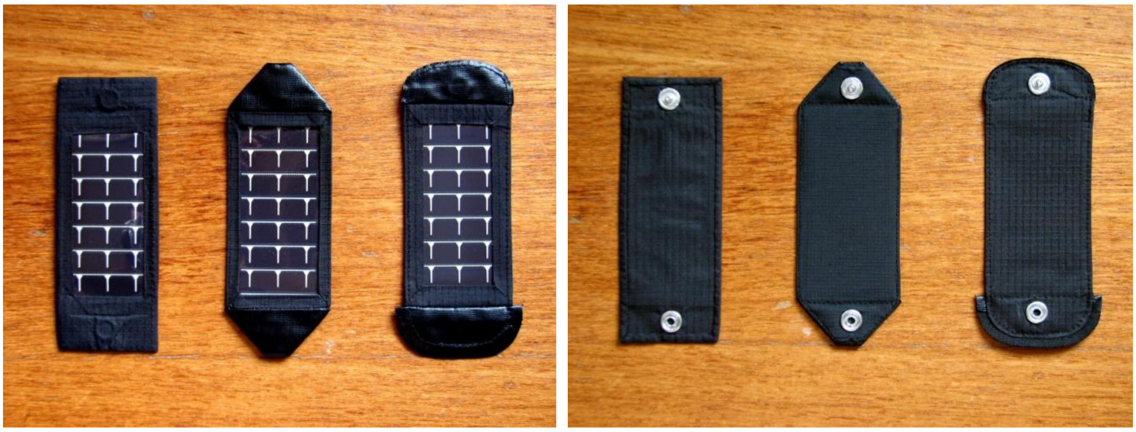


Figure 3.6 Solar panel's package by the embedding method – Front and Rear

<u>Array Formation</u>

In order to supply sufficient power to the device, a precise PV array needs to be designed on the basis of the capacity of the chosen solar panel (4.2V, 22mA). The nominal output power requirement for charging a mobile phone (3.7V, 850mA) is 3.1W (3.7V×0.85A). Theoretically, the targeted operating current of the PV system to charge a mobile phone device is 738mA (3.1W/4.2V). According to an average sunlight of 6~8 hours per day, 123mA (738mA/6hr.) ~ 92mA (738mA/8hr.) respectively is required to charge the mobile devise under these ideal conditions. Therefore, 4 (92mA/22mA) ~6 (123mA/22mA) solar films need to be connected to a PV array for this end use, and this PV array needs to be designed and developed to deliver the required current.

It is known that the same panels connected in series, parallel or combined will achieve different operating voltage and current. Three different circuit connections are calculated and compared on the basis of using six solar films, as shown in Table 3.2, according to the formulae used below:

$$\text{Power (W)} = \text{Voltage (V)} \times \text{Current (A)}$$

Equation (3.1)

$$\text{Resistance } (\Omega) = \frac{\text{Current (A)}}{\text{Voltage (V)}}$$

Equation (3.2)

$$\text{Charging Time (hr.)} = \frac{\text{Battery Current (MA)}}{\text{PV array Current(MA)}} \times 1.2$$

Equation (3.3)

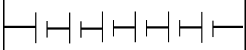
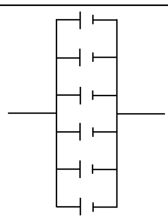
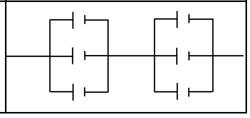
Connection Types	**Operating Voltage (V)**	**Operating Current (MA)**	**Resistance Ω (OHM)**	**Theoretical Charging Time (hr.)**	**Schematics**
Series Circuit	25.2	22	0.0009	38.6	
Parallel Circuit	4.2	132	0.03	6	
Combined Circuit	8.4	66	0.008	12.9	

Table 3.2 Calculation of three types of circuit connection

It is obvious that the operating current of the series circuit is too small to supply the required power. Hence, the modules in the PV array are designed and connected in the combined and parallel circuits, as shown in Figures 3.7 and 3.8. Respectively, after joining and making up in Chapter 6, practical testing of the solar prototypes in Chapter 7 revealed that the parallel circuit design is preferred for current efficiency.

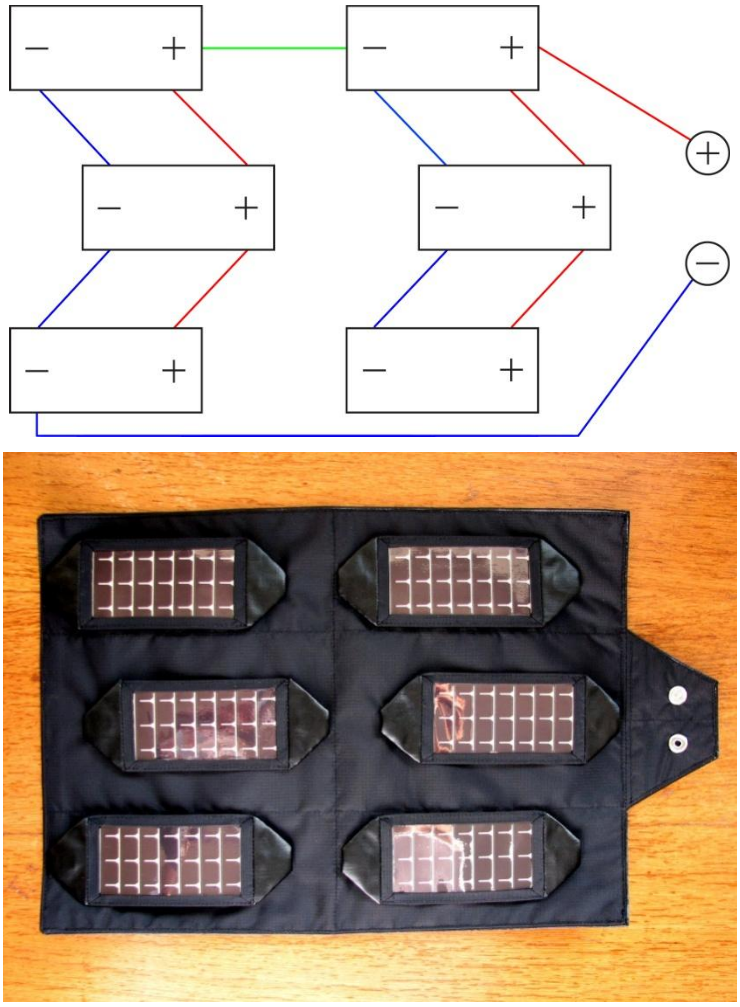


Figure 3.7 Combined circuit connection in the solar pouch

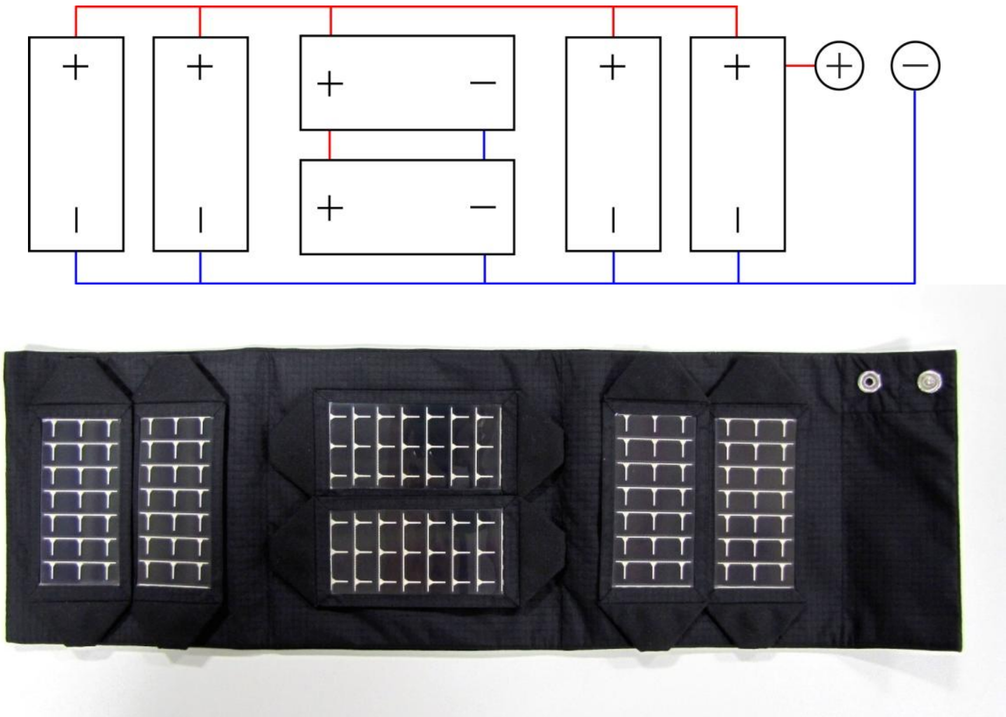


Figure 3.8 Parallel circuit connection in the solar pouch

3.1.2 Rechargeable battery

The data calculations shown in Table 3.2 are obtained for reference considerations. As it is known, in the shade or under an angle, radiation loss will reduce the PV panel's efficiency. In order to supply power independently of solar variation, batteries are used to store the solar-generated energy for use at will. These batteries are generally referred to rechargeable batteries which are known as secondary cells because of their electrically reversible reactions of charging and discharging. Since rechargeable batteries can be recharged very easily and used repeatedly, they have low cost and environmental impact better than primary cells due to higher life span. Although the technology behind the lithium-ion battery has yet to reach maturity, as rechargeable batteries, they are common in many consumer electronics. Li-ion batteries are the main choice for portable electronic devices because they have significant advantages; many shapes and sizes, lighter weight, higher energy density, low self-discharge and environmentally safe [39].

To be incorporated into clothing, the battery must also be small, thin and light weight for fitting in the designed pockets of the clothing and being comfortable to wear. At the same time, its capacity needs to match the maximum output for the end-use; called load compatibility. But the size and the weight of the battery are always directly proportional to its capacity. Therefore, to charge a mobile phone at 3.7V, 850mA, a rechargeable battery with capacity of 3.7V, 900mA or higher was chosen, which is also light and compact like any common mobile phone battery. Figures 3.9 and 3.10 show the dimensions of the chosen battery (3.7V, 900mA) being 49mm×30mm×6mm, and of (3.7V, 1100mA) is 51mm×32mm×5mm. The prior one is most suitable to fit with the PCB size in this project.

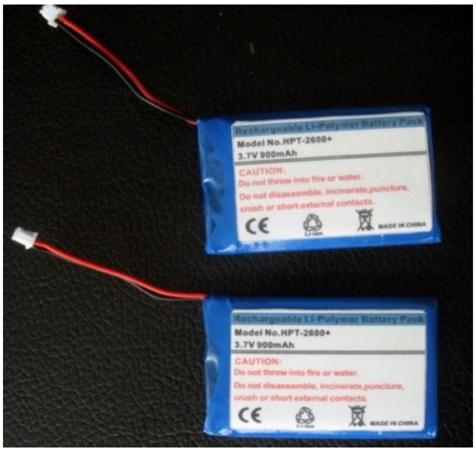


Figure 3.9 Li-Polymer Battery Packs, 3.7V, 900mA (most suitable)

Figure 3.10 Li-Polymer Battery Packs, 3.7V, 1100mA

3.1.3 Power Management Circuitry

Generally, the smart system requires higher power levels than it can be sustained by a PV array, therefore a rechargeable battery chosen needs to meet the peak power requirement when the PV array is recharging. Although a PV array produces power when exposed to sunlight, and the rechargeable battery can store the power as a backup, specific hardware is still required to ensure that the whole system is operating properly, such as; a power converter, a charge controller, disconnection devices, protective diodes and electrical conduction interfaces [40]. The integrated circuits (ICs) of this hardware are integrated in a small circuit board as shown in Figure 3.11; the rear is shown with the battery connected to it.

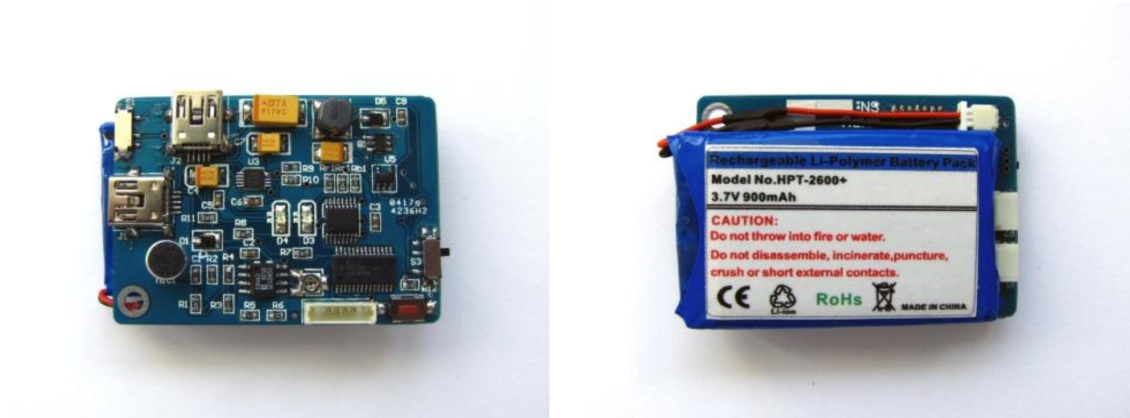


Figure 3.11 Power management circuit board – Front and Rear

<u>Power Converter</u>

The PV system is designed to power up portable electronic devices, such as a mobile phone, an MP3 or a PDA; as well as lighting up the LEDs in the clothing. For these types of devices, only direct current (DC) is consumed, whilst alternating current (AC) is usually required in building appliances as large PV systems where a DC-AC power inverter is used.

The chosen rechargeable battery has a 3.7V potential. This voltage will normally decrease when the battery becomes depleted. Then power would not be supplied to these devices when the voltage decreases. Since in ($P = V^2/R$), the R (Resistance) tends to be stable, then the power available to the load decreases as voltage decreases. So the lower voltage makes the system unusable under a normal load. DC to DC conversion is necessary at this point by using a boost converter, also called step-up converter. It is used as a voltage increase mechanism in the circuit known as the ‘Joule thief' for 'stealing' the remaining energy in a battery. But according to Conservation Law of Energy ($P = VI$), the output current is relatively lower than the input current.

In a PV array charging system, 4.2V output is enough for serving a 3.7V rechargeable battery. But for discharging from the rechargeable battery to a mobile phone, a boost converter needs to be designed to step up the voltage of the battery between 3.7V to 5V, and consequently the battery current is decreased from 900~1100mA to 666~814mA.

Charge Controller

If overcharged or overheated, Li-ion batteries may suffer thermal leaking and failure. Deep draining may affect the cell also. In these cases, a charge controller is incorporated in the system to protect the battery from overcharge and overdischarge.

The charge controller, also known as charge regulator or battery regulator, takes care of the rate of electricity flowing from the generator source to the battery and its load. By reducing or stopping the flow of electricity into the battery or load when they are full, the controller keeps the battery and load fully-charged but not over-charged. It can also perform a controlled discharge to prevent deep draining of the battery. Once a load has taken too much energy from the battery, the controller will stop the flow until sufficient charge is restored [41]. Charge controllers always appear in the form of a circuitry, in conjunction with solar generators or battery storage systems. Technically, this circuitry may consist of several semiconductor devices, or they are encapsulated in a single microchip in the form of an IC. The protective circuit of this type for intelligent management of battery charging is usually called a charge controller IC or charger IC [42]. Nowadays, 'integrated circuits' tend to mean monolithic ICs with the whole circuit in a single chip. So a charge controller IC can be miniaturised whilst having the same functions [43]. This has made it possible to design the entire power management circuit board smaller than half of a credit card, as shown in Figure 3.12.

Figure 3.12 Miniature PCB integrated with power converter and charge controller ICs

Disconnect Devices

Although a charge controller IC has been designed to manage the charging system for protecting the solar generator and battery pack, on and off switching peripherals are also important. A switch can break, connect or divert an electric current by manually operated electromechanical devices for ‘close’, ‘open’ or ‘change’ the electricity. In this application, it is a kind of interface between the wearer and other devices or between the user and the environment. It basically functions like a power switching control which we are using for almost all electric devices and equipments. It could be a toggle, a push-button or any type of mechanical linkage.

In new smart textiles and clothing, SOFTswitches [44] with conductive textile-based buttons and keyboards have also been developed [45]. But due to circuitry differences and complexities, they are only good to perform some simple actuations, such as on/off. Therefore, in this project, the mini toggle switch is preferred to be incorporated within the charging circuitry shown in Figure 3.13. Moreover, to let the wearer or user to visually know the charging status of the system, two miniature light-emitting diodes (LED) are interconnected synchronously within the charge control IC to indicate performance. One is a green LED to show the charging status, another is a red LED to show error, as seen in Figure 3.13.

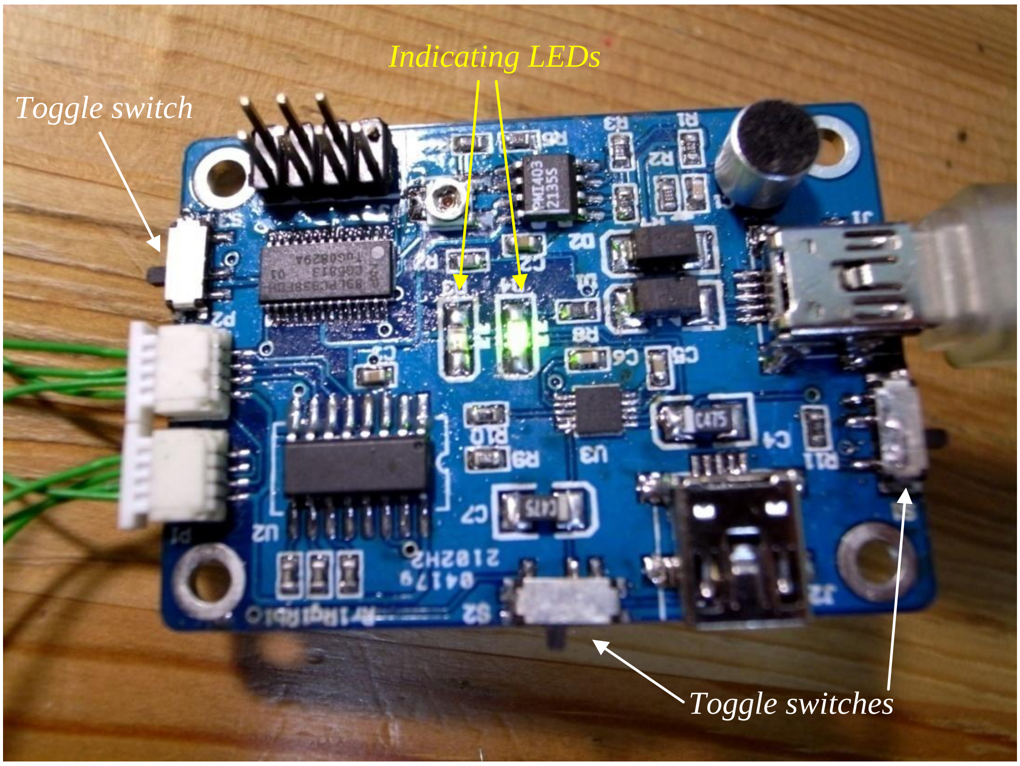


Figure 3.13 Toggle switches and indicating LEDs interconnected within the charge controlling IC

Protective Diodes

The most common function of a diode is to allow an electric current to pass in one direction, but block current in the opposite direction. This important rectifying characteristic is used in the PV system to prevent a reverse flowing through the PV modules, for instance, blocking-diodes to prevent battery drain during discharging. With the advantages of having lower junction voltage and greater switching speeds, Schottky Barrier Diodes (SBDs) are ideal. Figure 3.14 shows that every SBD needs to be connected between each solar panel and the PCB. Since the PV array and rechargeable battery pack might be assembled in different places in the clothing, the position of these SBDs is challenging.

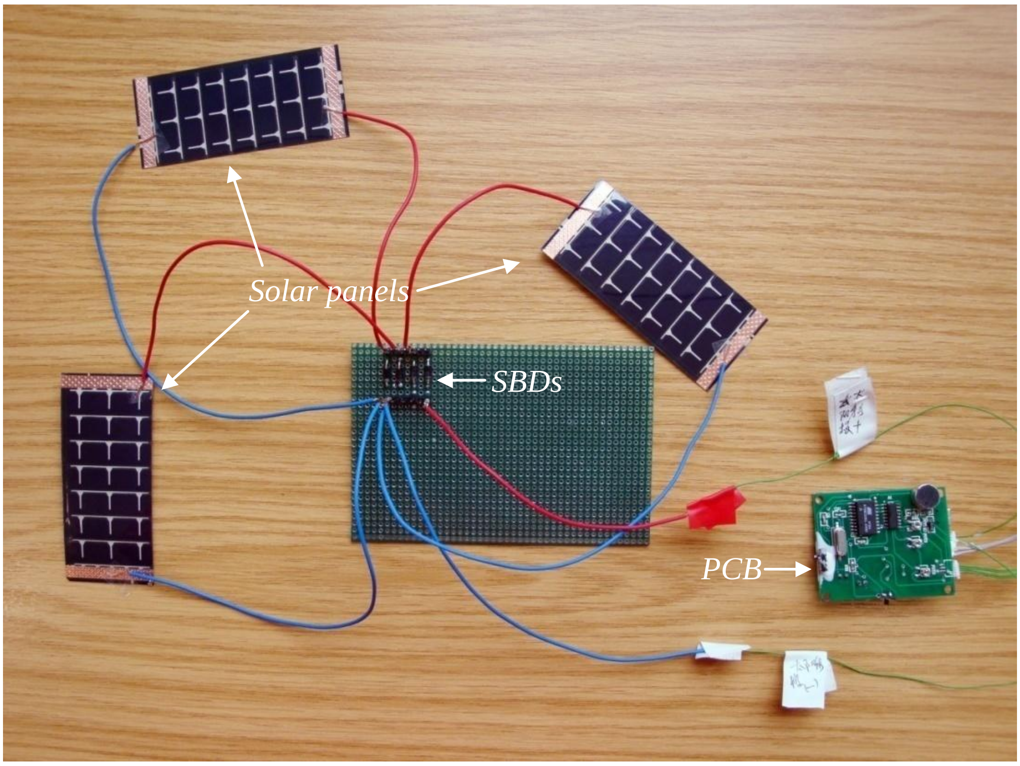


Figure 3.14 Connection of the SBD between each solar panel and the PCB

Electrical Conduction Interfaces

From the PV array, to the rechargeable battery and power management circuitry, and to electric devices, three parts are needed to form the whole energy harvesting system, and accomplish the power accumulation, storage and utilization processes. Since they are of totally different formation and fabrication, the linkages are important for connecting each part to the whole system.

This interface usually consists of connectors and cables. Any failure of a connector or a cable will cause the entire system to fail. Therefore, careful consideration needs to be taken when components are chosen and when designing their connections. Commonly used connectors are terminal blocks, crimp-on connectors, plug and socket connectors, and the like. Electrical cables are always wiring with cylindrical, flexible strand or rod of metal for soldering, crimping or other methods to bear mechanical loads and carry electricity and telecommunication signals. Insulating and jacketing is an important requirement of electrical cables. As an industry standard for connection and power supply between electronic devices, USBs (Universal Serial Bus) 2.0 were applied as common interfaces on the power management circuit board to connect with the PV array and/or mobile phone, as shown in Figure 3.15. For the connection between the rechargeable battery/LEDs and the circuit board, mini plug and socket connectors were specially used, as shown in Figure 3.16.

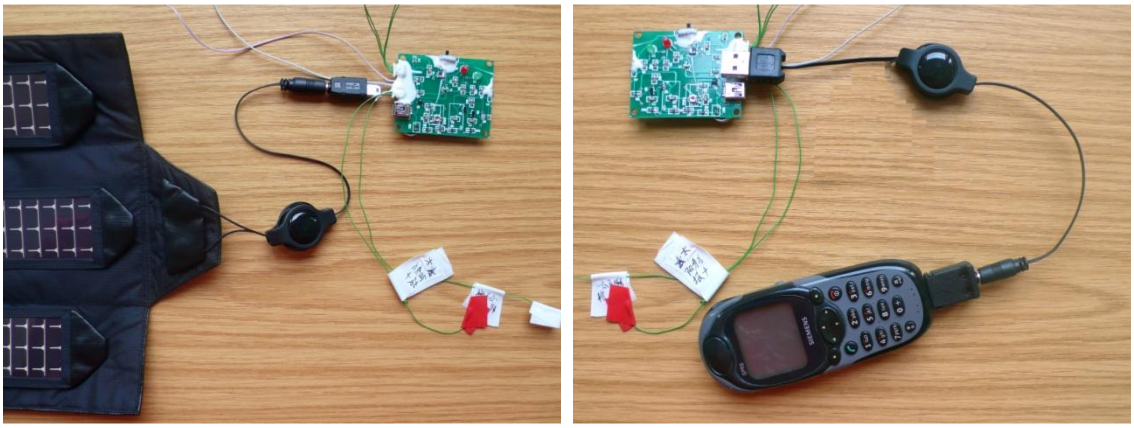


Figure 3.15 USB connectors

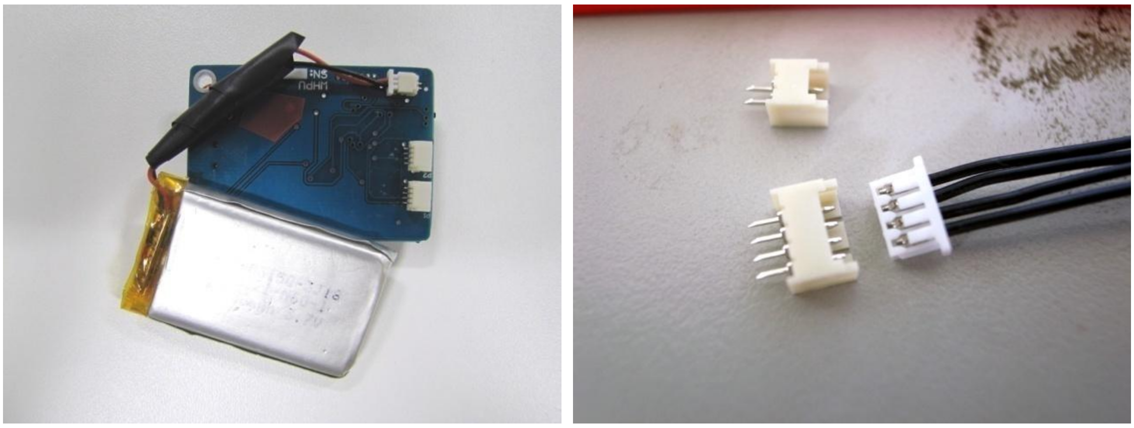


Figure 3.16 Mini plug and socket connectors

In the smart clothing of this project, textile-based wiring has been used to try to replace traditional wires and connectors by conductive fabrics and snap fasteners, such as the connection of PV modules shown in Figure 3.17.

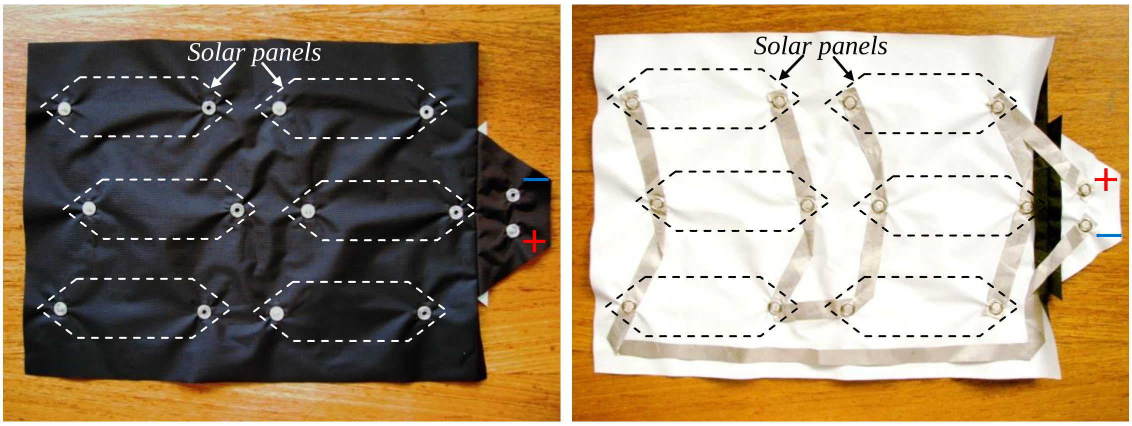


Figure 3.17 Connection of PV modules by conductive fabrics and snap fasteners

3.2 Light Emitting — LED and Fibre Optics

With large energy consumption and over-illumination, people start to consider more efficient means of utilizing natural resources for a sustainable future [46]. Although solar energy has the potential to become a major and sustainable energy resource, due to efficiency limitations, global generation of solar electricity is still small compared to normal consumption. Consequently, rational use of energy is as important as harvesting energy. Different energy-efficient lamps have been developed for more than two decades, from traditional incandescent light bulbs to compact fluorescent lamps (CFLs), then from energy saving halogen lamps to light-emitting diodes (LEDs). LEDs are the newest and best environmentally friendly lighting method. According to the Energy Saving Trust, an LED lamp uses only 10% of power compared to a standard incandescent bulb, where compact fluorescent lamps use 20% of power and energy saving halogen lamps use 30% of power [47].

In solar energy harvesting, day light is utilized to achieve electric power. We then utilize this electrical energy to produce light. This application of light is called lighting or illumination and can be used in a number of ways, one of which is in SMART clothing. As a visual interface, the wearable photonics can be as liquid crystal displays (LCDs) or LEDs and fibre optic displays (FODs). Since wearable LCD panel or film used on clothing is considered neither flexible with poor angle visibility, nor lightweight with bulky characteristics [48], LEDs and FODs were chosen for the mood changing objectives in this project.

3.2.1 Light-emitting diode (LED)

As a semiconductor device, a light-emitting diode (LED) emits light when conducting electric current. It’s an optical and electrical phenomenon which is called electroluminescence (EL). EL is one of the types of luminescence, in contrast with incandescence which is another way of producing light from heat. Luminescence can also be caused by chemical reactions (chemiluminescence), sound (sonoluminescence), photons (photoluminescence) and so on [49].

For the purpose of designing the smart energy harvesting system for releasing energy in the form of electricity, EL technology has been investigated. There are two kinds of devices to display EL. EL displays (ELDs) are matrix-addressed devices which need the impact of high-energy electrons accelerated by a strong electric field. Since ELDs have the basic structure of at least six layers, they are best performed as backlighting in panels or information displaying films, even in advertising billboards and signs. Another device is the LED. LEDs are discrete devices that produce light at a lower energy level [49] [50]. LEDs have many advantages which are applicable in clothing as revealed in this project, such as, lower energy consumption, small size, discrete and direct application, fast switching, robustness, longevity, durability and reliability. Furthermore, they have become multicolour and very bright since Nick Holonyak Jr.'s invention in 1962 [51].

LEDs are operated at low to high power levels and emit different lumens, depending upon their end use. The most suitable LEDs for this project have been investigated with the consideration of several parameters. First of all, miniature single-die LEDs are preferred with a voltage rating from 2V~5V for low energy consumption. Since our smart system is based on textiles and clothing, the multicoloured LED with high lumen but small size is found as the ideal choice of lighting/colour changing source. A number of tradeoffs are necessary since the larger the LED the higher the brightness, and also the luminous intensities for different colours in the same sized LED are different. This investigation included searching, comparing and testing the performance of different LEDs, and concluded that 5mm ultrabright white LEDs and superbright RGB LEDs are most suitable. The main electro-optical characteristics of these LEDs are shown in Tables 3.3 – 3.5.

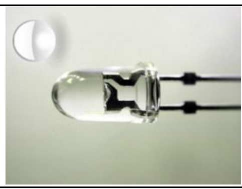
Item	Ultrabright LED Nichia NSPW-500GS-K1, 5mm Water clear lens 15˚					
Emitting Colour	**Forward Voltage**		**Forward Current**		**Luminous Intensity**	
	Typ. (V)	**Max. (V)**	**Test. (mA)**	**Typ. (mA)**	**Typ. (mcd)**	**Max. (mcd)**
White	3.2	3.5	20	30	31000	44000

Table 3.3 Electro-optical characteristics of ultrabright white LEDs (Courtesy of LED-TECH.DE)

Item	Superbright RGB LED 4 pin, Common Anode, 5mm Transparent lens 30˚			
Chip Emitting Colour	**Wavelength (nm)**	**Forward Voltage Typ. (V)**	**Forward Current Typ. (mA)**	**Luminous Intensity @ 20mA (mcd)**
Red	630	2.0	25	1500
Green	525	3.6	30	1500
Blue	470	3.6	30	1500

Table 3.4 Electro-optical characteristics of superbright RGB LEDs (Courtesy of LED-TECH.DE)

5mm RGB Water clear lens 				35~40˚ 	
Item	**Chip Emitting Colour**	**Wavelength (nm)**	**Forward Voltage Typ. (V)**	**Forward Current Typ. (mA)**	**Luminous Intensity @ 20mA (mcd)**
540R2GBC-CA (Common Anode)	Supper Red	625	2.0	30	1500~2100
	Pure Green	525	3.5	30	4200~5800
	Royal Blue	460	3.5	30	1100~1500
Total brightness of this LED is up to 9400 mcd, mA test = 60mA (20mA for each chip).					

Table 3.5 Electro-optical characteristics of superbright RGB LEDs (Courtesy of HEBEIltd.cn)

<u>Power Source Consideration</u>

The power source is an important factor in designing of the system. Similar to other diodes, the current and voltage characteristics of an LED are interrelated with each other. A small change in voltage could cause a large change in current. Potentially, the LED will be damaged or destroyed if its maximum voltage/current is exceeded. It is therefore important to have the right, reliable and stable power supply. For LED flashing, a switched-mode power supply is used. According to the power management circuitry of 3.7V of the chosen LEDs, a constant current power supply of 30mA has been used in the static lighting mode, and 40mA current power supply in the dynamic/flash lighting mode, which is tested and described in Chapter 7.

Electrical Polarity

Current flows in the correct direction when the current flows across the p-n junction from positive to negative. If the voltage is of the reverse polarity, LED will not work or may get damaged. Although the manufacturer will normally point out the polarity and colour of the LED in the product datasheet, careful design and correct connection is necessary in the PCB and in the garment making process. Figure 3.18 shows the positive and negative connection of the mini connector and the single-colour LED leads used in the system. With a common anode (CA), Figure 3.19 shows the colour correspondence from the RGB LED leads to the mini connector via wire extension.

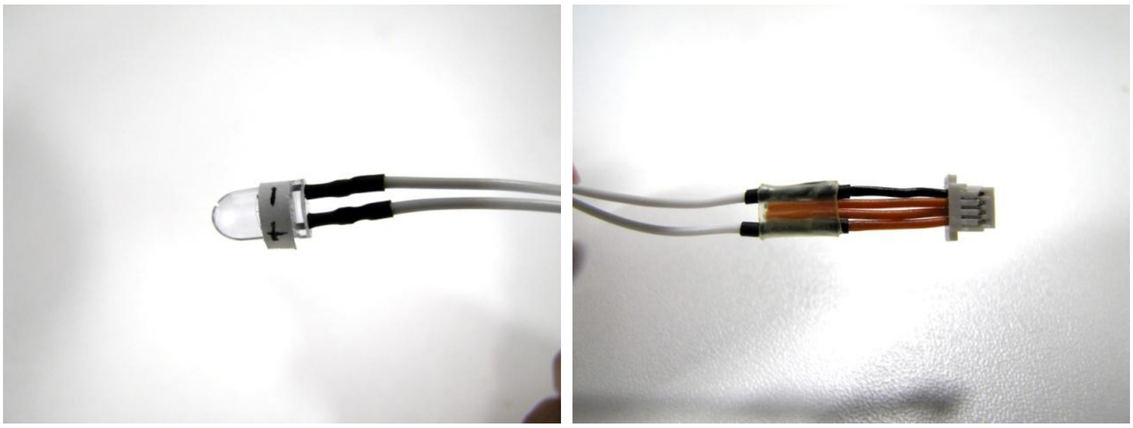


Figure 3.18 Connection of the single-colour LED and the mini connector

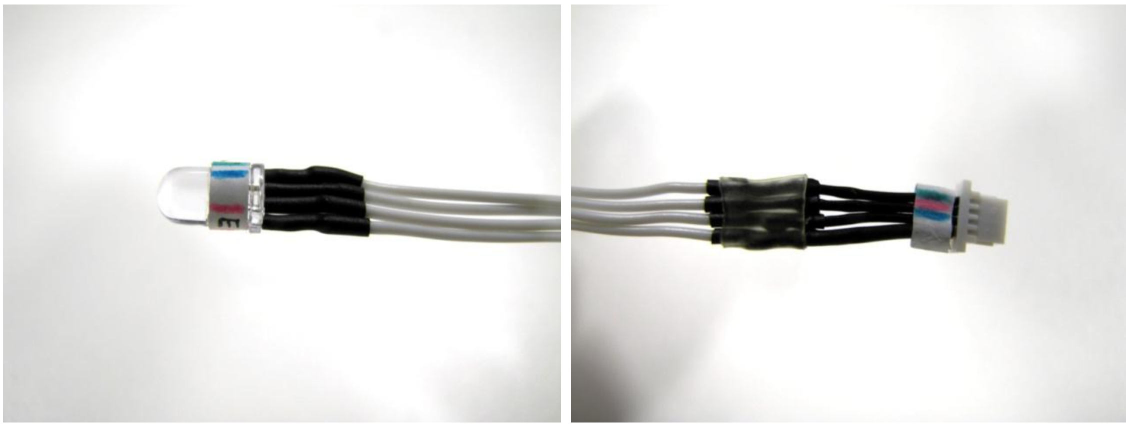


Figure 3.19 Connection of the RGB LED and the mini connector

Colour lighting change

Testing the luminous intensity of the single colour LED was done by operating gradual voltage changes, and hence the highest lumen of the ultrabright white LED used in this project was established. Based on colour theory and LED technology, white light can be formed by mixing different coloured lights. A typical method is to use red, green and blue (R+G+B). The chosen four-leads RGB LEDs contain red, green and blue chips in one entity. With careful design, they can easily change colour under control and can provide a wide choice of colour. To fulfil the smart concept for this clothing system, a bespoke RGB LED based colour blending and changing programme has been designed to accommodate smart dynamic colour changing according to voice stimulus. The colour changing programme will be described in Chapters 4 and 7.

3.2.2 Fibre optics

Fibre optics is the field of applied science and engineering based on optical fibre design and fabrication. As a flexible and transparent fibre, an optical fibre acts as a waveguide, or "light pipe", to transmit light between the two ends of the fibre [52]. Optical fibres are used in a variety of materials and at various types and sizes for different applications. With these properties, optical fibres are widely used in fibre optic communication, fibre optic sensors, and also in illumination applications. A combination of fibre optics and LEDs to construct a SMART clothing system is novel and fashionable.

Typically optical fibres are made of very fine pure glass (silica) for good internal reflection and coated with polymers for protection. This type of glass fibre optics is usually applied for data transmission, imaging and sensing. Fibre optics used for lighting is relatively less delicate and precise with regard small optical defects [53]. Plastic fibres, mostly polymethyl methacrylate (PMMA), are the most common materials being used. With an reflection angle of 35 degree and operating temperature between -40 to 82.2 °C, plastic fibres cannot be used in electron transmissions because of their limitations in dimensional stability and environmental durability [54]. Nevertheless, for photon transmission in the visual spectrum, plastic presents similar characteristics to glass. In this project, fibre optics of the plastic fibre type has been chosen with advantages of flexibility and ease of end-finish.

Another advantage of plastic optical fibres is in their light emission along its axis, as side glowing or discrete emission (sometimes called sparkling emission) features, as shown in Figure 3.20. The side lighting characteristic exhibits more possibilities for applications in solid architectures as well as in textiles and clothing.

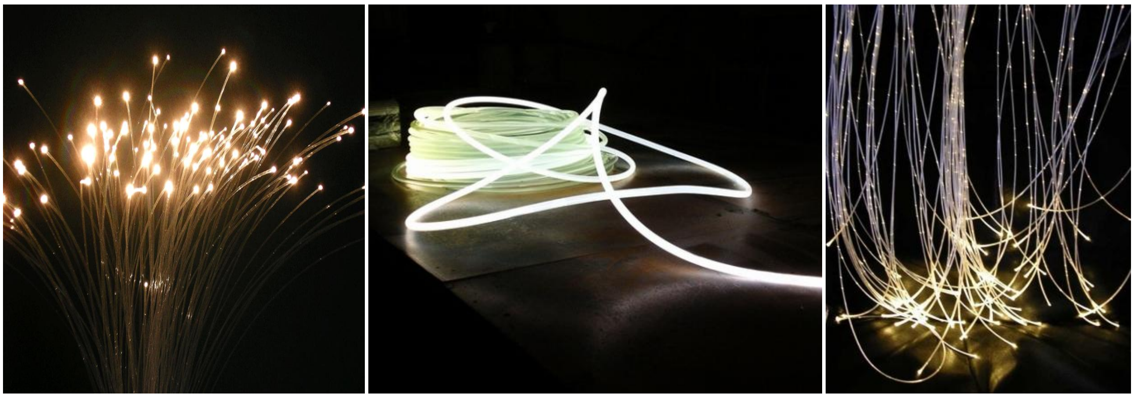


Figure 3.20 End emitting, side glowing and sparkling optical fibres (from left to right)

Fibre optics for lighting in architecture has been used in a wide range of size from thin 0.75mm to thick 6mm or higher (Figure 3.21). They are multi-strands or multi-cores with slightly larger optical source ports. The size which can be chosen to fabricate wearable textiles and clothing is however more limited and important. First of all, the optical fibre must be as fine as a typical yarn. Currently, the thinnest optical fibre in the market is 0.25mm (Figure 3.21), close to a conventional nylon-like yarn. In fact, it is not possible to make an optical fibre to behave like a textile fibre or yarn because its structural mechanics are radically different in properties such as elasticity, flexibility, bending, resistance, softness, etc. which suit the weaving, knitting and wearing processes. Therefore, modification by chemical, mechanical and other means is important for increasing the optical fibre’s structure for use as a fabric, and at the same time perform the optimum illuminating properties [55].

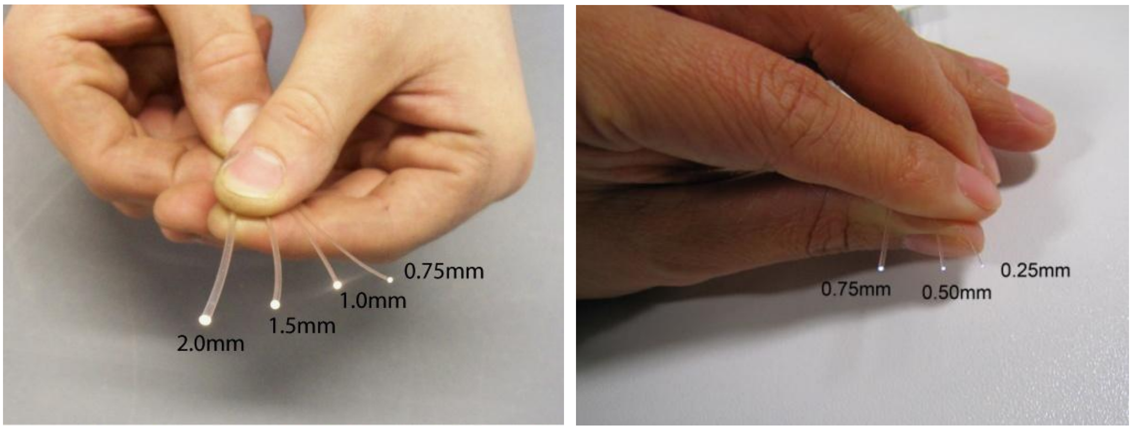


Figure 3.21 Optical fibres in different sizes

A typical fibre optic lighting system consists of three main parts; an illuminator as the light source, a harness with holder and coupler, and an end fitting structure.

Illuminator

It is necessary to supply a light source to the fibre optics for illumination. Supplying devices could be light-emitting diodes (LED), laser diodes, halogen lamps or even solar radiation. But the key element for considering the light source for wearable end-uses is the compromise between dimension and efficiency. Obviously, this kind of lighting source needs to be embedded in the clothing and hence needs to be small and lightweight but effective enough to illuminate a fabric more than 1 meter wide. The superbright LEDs of 5mm diameter are most suitable as already stated, shown in Figure 3.22. These LEDs are compact, have high-efficiency and low cost, and at the same time have multi-colour possibilities.

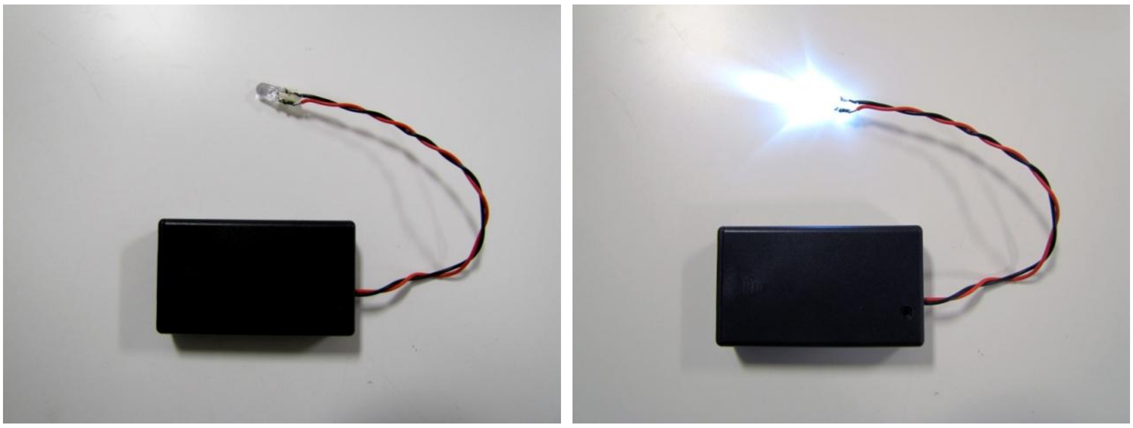


Figure 3.22 5mm superbright LED as the illuminator

Harness

Optical fibres for lighting are usually assembled in the form of a bundle as shown in Figure 3.23, either in solid cores or fibre strands to be housed so that they are connected with the illuminator. Such bundles are used to gather the light and transmit light wherever is needed. Therefore the finishing of the optical fibre bundles, along with the connection system between the bundles and the LEDs are important for forming an entire harness.

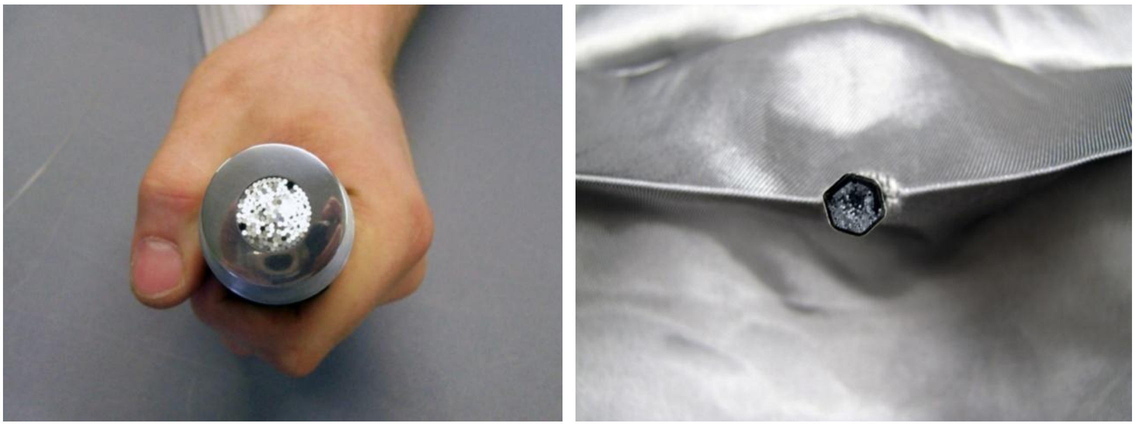


Figure 3.23 Common thick ferrule and special thin ferrule to assemble the optical fibre bundles

The optical fibre bundle is made with a specialized instrument. The fibre ends are placed into a special holder and cut with a precise cleaver perpendicularly. This termination allows the fibre bundle to be held precisely and securely, as well as being ready to connect with an illuminator. As discussed, the illuminator efficiency is related to the illuminator type and the supply of power. For example, a 5mm superbright LED can be powered by a 3.7V rechargeable battery, as already discussed. Thereafter, the efficiency of the fibre optics depends on effective connections. Basically, a connector is designed as a coupler as shown in Figure 3.24. It is a rigid cylindrical barrel surrounded by a dark sleeve that holds the barrel to form the connecting socket between the fibre optic and the power source. The connecting mechanism can be pushed and clicked, or turned and latched. Thus, the optical fibre bundle is in contact with the illuminator permanently.

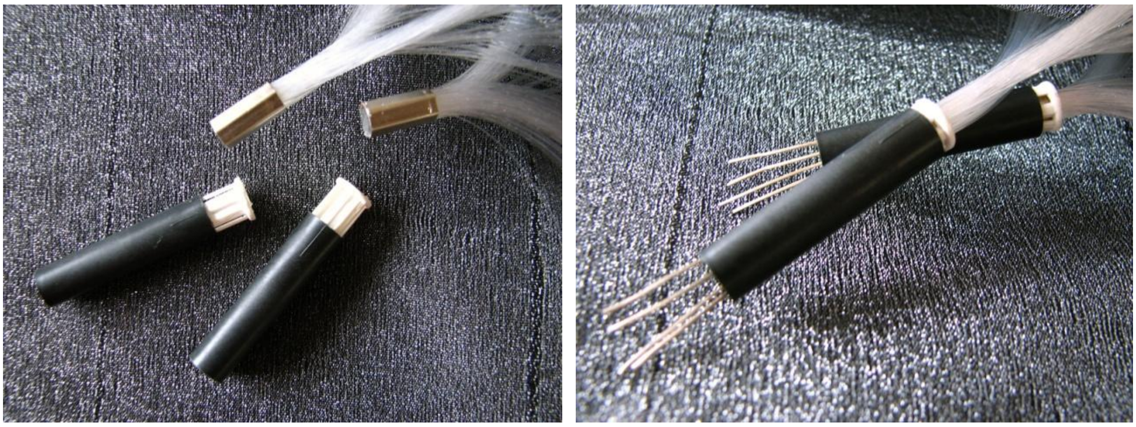


Figure 3.24 Connecting sockets to harness optical fibre bundles and illuminators

Fitting and structure

The optical fibres are limited for illumination only at their ends which need to be threaded and mounted in a particular way for lighting up when connected with the illuminators. Instead of being constructed into the fabric and clothing, they have been used in architecture and interior design, such as the Star Cloth shown in Figure 3.25.

Figure 3.25 Fitting of end-emitting optical fibres in Star Cloth [56]

The side glowing or sparkling optical fibres are magnifying the illuminating surface of every single optical fibre as it is shaped over an object. In this case, the fine sparkling optical fibres are put together to form a fabric. Figure 3.26 shows these fabrics which exhibit remarkable visual presentation and have multi-functional possibilities.

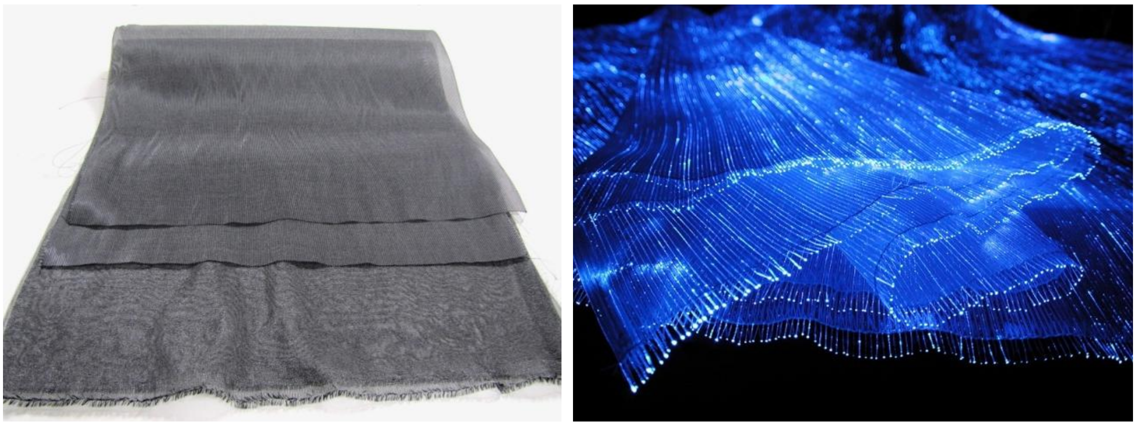


Figure 3.26 Structure of sparkling optical fibres in the luminescent fabric [57]

3.2.3 Smart electroluminescent fabrics

Due to their economy and low power consumption, LEDs and fibre optics can be used in photonic textiles. This concept is used for this project. They are composed by interweaving with conventional textile yarns, and have properties similar to a fabric like flexibility, elasticity, resistance, softness and so on. They can also be made in different weights, colours and composition. The structural performance of fibre optics is favoured for making a flexible and continuous woven fabric over having layers of electroluminescent dye coatings on a fabric substrate. LED technology is used to emit good visible light, even selecting or changing colour at will or by programming, as will be discussed later. Luminex is one of such electroluminescent fabrics with good potential for clothing end uses.

In this project, the electroluminescent fabric has the following attributes:

- Multi-functional performance based on textile features, such as light and colour;
- Changeable properties by controlling a microchip;
- Composition for energy exchange and utilization, as in the case of our energy harvesting system requirement, transferring the stored electric power to light;
- Specific interface designed to change colour by reacting to any stimulus from the environment by programming, such as in human’s mood changing by voice data analysis which is developed as below.

3.3 Information Technology; Mood Changing

Research in SMART textiles has defined “smart” as sensing and responding in a controlled manner to environmental stimuli which comes from mechanical, thermal, electrical, chemical or other sources [30]. The electroluminescent fabric system under development which consists of LEDs and fibre optics can emit light by connecting with an electrical part. Hence, the system is more than a fabric, and it becomes “smart” by the integration of electronics.

According to our SMART clothing design, smart fabric can be used to sense, react and activate a specific function, i.e. change of colour. Firstly, the essential sensing part is designed. Then through data processing, analysis and evaluation, the activated function is performed by actuators in real time or by a programme which forms an information system. Therefore, our smart clothing system is working intelligently by reacting to a human’s sensation and perception. This smart clothing system can not only supply light through PV energy storage, but also change colour as the result of mood/physiological changes of the human wearer, by voice data analysis.

3.3.1 Mood changing as physiological and psychological changes

Textiles and clothing are no longer fulfilling conventional needs of comfort and protection. Our SMART clothing system is optimized with advanced smart functions.

In this development, the clothing becomes dynamic with light and colour changing depending upon the mood of the wearer.

Mood, as a state of mind or emotion, is often thought as a psychological reaction to external stimuli. Nevertheless, to be considered as a long lasting emotional state, but less specific, less intense than the concept of an emotion, recent scientific findings define the everyday mood as biopsychological in nature. In this definition, mood is the general index of both physiological functions and psychological experiences [58]. Unlike the case of acute and emotional feelings as in fear or surprise, generally speaking, mood can be classified in two main types; positive or negative, or speaking of being in a good mood (happy) or in a bad mood (sad). As the arousal of physical activities, mood is also interpreted by high/low energy and tension [59].

As the window to our physical and biological state, mood is internal and subjective which can be inferred from body language, such as behaviour, posture, speaking, etc. Hence, hang up or down lips, relaxed or tight shoulders, swift or slow response, high or low tone of voice, and the like are typical but different physical signs of mood. Psychologically, we evaluate the positive signs as good mood which can be indicated as happy, powerful, active, and so on. In contrast, the negative signs are described as bad mood like sad, strengthless, dull, etc. Positive moods are regarded as calm and relaxed with slow responsiveness and low voice. But negative moods are the opposite of being fearful and nervous with fast responses and high voice. Anyhow, energy and tension are the main components that reflect human moods. Consequently, moods related to high or moderate energy and low tension are prone to be positive. Negative moods indicate low energy and high tension [58].

Although mood is a lasting effect, it is also a variable state due to external changes and internal feedback regulation. Like a clinical thermometer, mood is changeable and it reflects on all the internal and external events that affect us. Because of complexity and limitations, the profound psychological cause and effect of mood are still being researched. But on the level of *consciousness*, we can recognise mood from basic physiological implications and psychological experiences.

3.3.2 Sensation and perception —Audition and Vision

One of the key components of consciousness is sensation, the processing of senses. Our senses are important physiological capacities to let us experience things before learning. If we could not experience things, the world including "the self" would not be discovered. Senses are transducers from the physical world to the mind. Sensory information is gathered and sent to the brain, then processed by perception. Perception is the way we organize and interpret the sensory information we receive, and in turn become aware or understand the change of the environment around us. From sensation to perception, the whole process can be the study of our mood in both physiological and psychological aspects, depending on the relationship between environmental events and our experience of those events.

There are three elements involved in the reaction between human and environment [60]:

- The first is the stimulus that arouses a sensation, both physical characteristics and psychological attributes;
- The second is sensory receptor which receives the stimulus and reacts in motion;
- The third is sensory perception which is composed of sensations to which the brain reacts, either due to prior experiences or due to our current physiological state.

A sensation occurs when a stimulus activates one of our receptors. And when we apply our experience to interpret the activated sensation, thus a perception occurs. It's naturally a dynamic chain reaction. In other words, sensation and perception are how we sense the world and how our body interpret these senses [61].

In different receptive fields, different senses are presented. The basic five senses are vision, hearing, touch, taste and smell which are well known. In fact, each sense is important in our life as a whole industry is built on specialized sense(s), for example, radio for hearing, TV for both vision and hearing, textiles for vision and touch, cooking for taste, fragrance for smell, etc. In this smart clothing system which is made by electroluminescent fabrics, auditory sensation and visual perception are being involved.

<u>Auditory sensation</u>

Hearing is the sense of sound perception. The physical stimulus for hearing is a sound wave which is created from a vibrating source. For humans and many species, the receptor for any sound is the ear. An auditory system can be considered in which information is arrived at the ear as a sound wave propagates through air, and within the ear it is transformed into neural signals in response to that sound. Then these nerve impulses travel to the brain where they are perceived. Hence, hearing is not only a purely mechanical phenomenon of wave propagation, but it is also a sensory and perceptual event.

As a signal is perceived by one of the major senses, sound is used for detecting danger, navigation, communication, etc. The scientific study of human sound perception is directed more on the physiological and psychological responses associated with sound, including hearing, speech and even music. For example as shown in Figure 3.27, when this signal is produced by a human voice, we cannot only perceive different qualities of voice as pitch, loudness and timbre, but also infer human moods and emotions such as happiness or sadness, anger or calmness. This is used in our project. Music is an art form created for hearing sensation and perception, and has long been used to help people deal with their negative emotions.

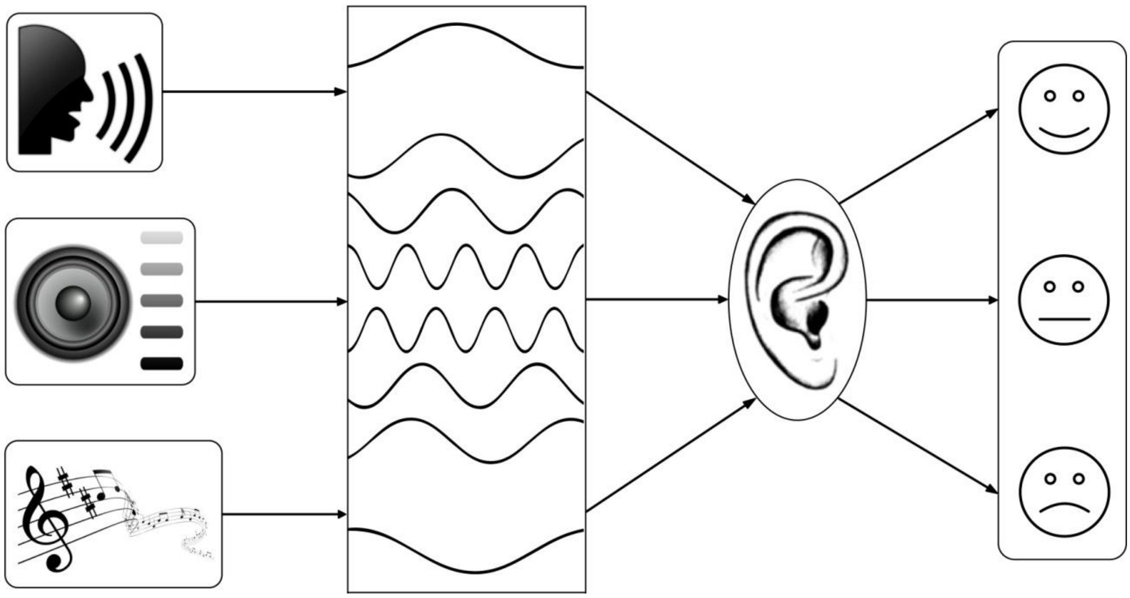


Figure 3.27 Hearing sensation and perception through a human's ear

Visual perception

Vision or sight is the ability of the eye(s) to detect images of visible light on photoreceptors in the retina of each eye, then responding by producing nerve impulses for varying colour and brightness. In visual perception, humans can interpret information and surroundings from the effect of visible light reaching the eye. This visible light is actually the portion of the electromagnetic spectrum that is visible to the human eye. In the optics field, this spectrum contains information about the distribution of light energy for various wavelengths. When the light is perceived by a human, colours are naturally emerged as coherent phenomena. Light vision is explained as colour vision by observing differences in colour as we distinguish the forms in objects [62].

One of the leading theories of how we see things in colour (colour vision) is the Trichromatic theory. Most human colour perceptions can be generated by a mixture of three primary colours, in an additive or a subtractive process. Light mixtures behave differently, as we call additive colours with the three primary colours; red, green and blue (RGB), as seen in Figure 3.28, and we call subtractive colours with the three primary colours; cyan, magenta and yellow (CMY), as seen in Figure 3.29. Two primary colours can mix almost all visible colours in different processes.

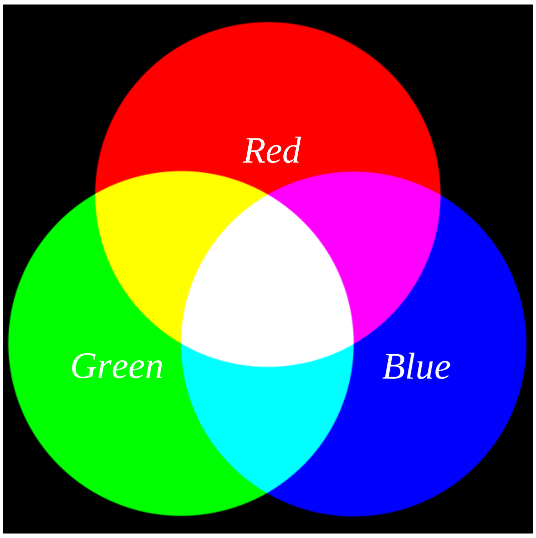


Figure 3.28 Three primary additive colours (RGB)

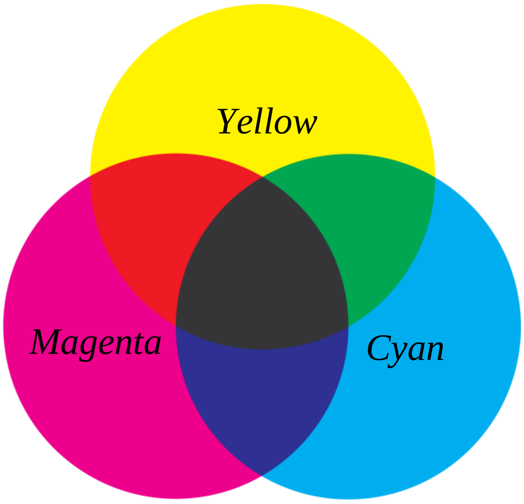


Figure 3.29 Three primary subtractive colours (CMY)

An interesting application of the principles of colour sensation and perception is how we dress ourselves or decorate our environment. In the same way as lines and shapes, colours play a vital role in projecting an image and creating a mood. For example, blue or purple colour is cool and related to a calm or bad mood; but the exciting or happy mood is indicated by warm red or orange colour.

<u>"See with your ears"</u>

Is there any connection with what you hear and what you see? Hearing and vision are seemed to be different senses and are perceived in different parts of our brain. But in the interactivity in the psychology of mood states they can be correlated. Basically, our sensations are interlinked. A good clue to different mood expression is by considering a voice or music which is not only auditory but also visual. It is somewhat like a "joined sensation" [63]. For example, sound often changes the perceived hue and brightness with the description that loud tones are brighter than soft tones, or lower tones are darker than higher tones.

3.3.3 Smart information systems

According to the physiological and psychological human cognition, the basic idea of sensation and perception are researched as mood changing theories and further combined with information technology to form a smart clothing system. Information exists in the physical environment and can flow from this environment into a computational system via sensory transduction. We take primary sensation as physical events in the nervous system to signal, store and process the information in a computer; and perception as physiological information coded in brain nerves. Therefore, mind and brain are like software and hardware of our prevailing smart computational system [63]. How can clothing behave intelligently with hearing; understanding and presenting back the information to the wearer? Creativity starts with the processing of a human's sensation and perception and in turn being feed back to the human as information or an action. These are essential elements in intelligent technology. Our smart clothing system is built under this working concept with three activities as shown in Figure 3.30.

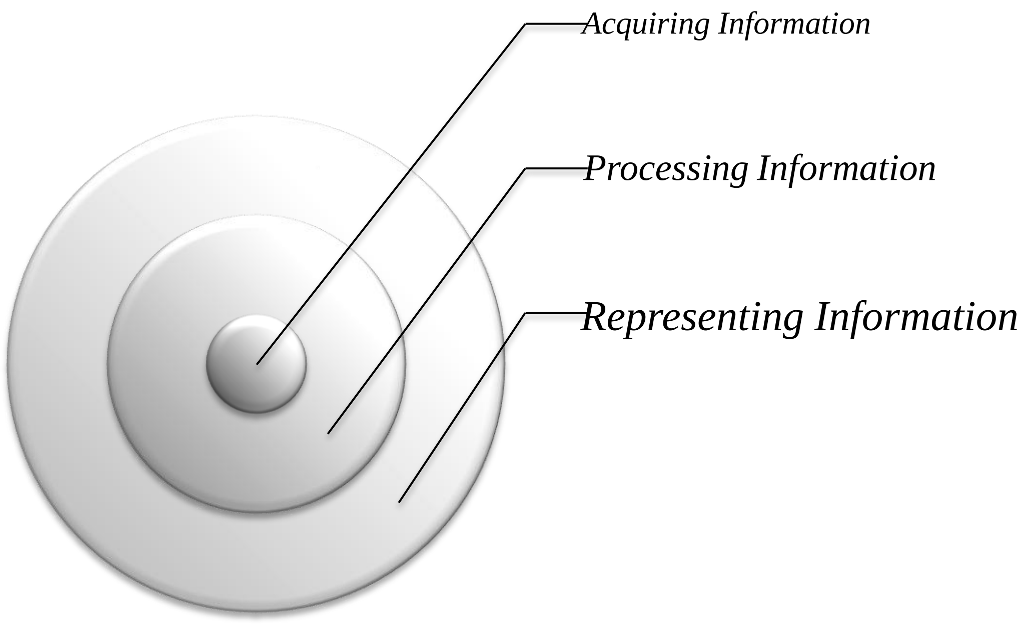


Figure 3.30 Smart information systems

Acquiring information

Sound is consequently a signal to convey a human's mood state. The initial question is how do we obtain this signal and how can we measure it? Theoretically, a sound source radiates power and results in sound pressure. This cause and effect is an analogy to a heat radiation and temperature effect [64].

In the first stage, we take our voice as the external stimulus for our smart clothing. The important part to collect information from this stimulus is related with the transduction design in acoustics. A transducer is the device for converting one form of energy into another. In acoustics design, it means converting sound energy into electrical energy (or vice versa). As shown in Figure 3.31, the transducer applied in the sensory part of our SMART clothing system is a miniature microphone which converts a sound pressure wave to an electrical signal by means of electrostatics. As the sound wave strikes the microphone's diaphragm, it vibrates and induces a voltage change. This is similar to how a human's ear works. The pressure variations on the eardrum we perceive as sound are the same as the detected pressure variations on the diaphragm of a condenser microphone. Obviously, the structure and function of a human ear are technically more difficult and complex. And its ability to sense the sound is done by multiplexing of loudness, pitch and timbre. In this research, sound loudness is taken as a measure of someone's mood, as will be discussed later.

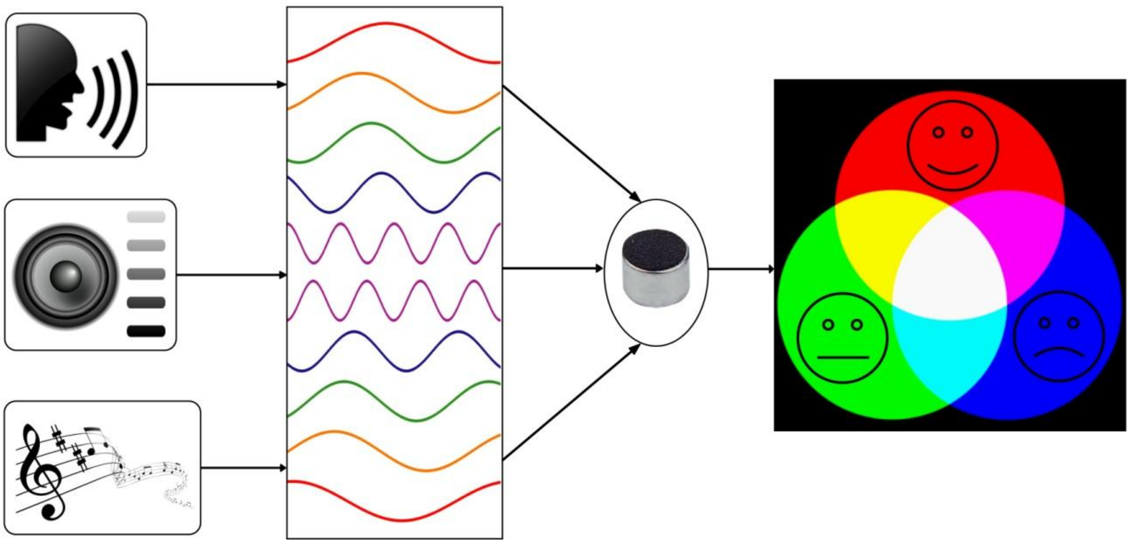


Figure 3.31 Hearing sensation and perception through a miniature microphone

Processing information

Consequently, sound signals are perceived as loudness (volume), and are objectively measured as sound pressure (voltage); theoretically calculated for interpretation as sound intensity (acoustic power). Although it seems not difficult to acquire sound information by a microphone, just like we take our hearing sense for granted, the information technologies to acquire, process and store this data are not simple. The signal is converted to audio by controlling any noise and interaction with other components, this is challenging. With the aid of computational technology, a microcontroller is used in a purposely designed and made voice control PCB, to process voice signals and handle the stored data for achieving an organised output as stated below; very much like our perception organizes and interprets sensory information.

At the foremost, the energy conversion is based on the intensities of sound signals which are graded to several levels of volume (sound loudness) and converted to different range of voltages (sound pressure). Here LEDs are being used as effective devices to display the sound pressure variation, so that the converted voltages of the sound signals are in the range of 0V to 3V in LED power level. Each sound volume corresponds to a voltage. For instance, the lowest volume is 0V, the highest volume is 3V. But the signals that are being detected by the microphone are very low (between 0mV to 50mV); therefore, a Microchip Unit (MCU) with an LED Driver IC and Audio Operational Amplifier is designed in a PCB and programmed to amplify the micro current to the required voltage.

Practically, the sound pressure we hear or measure with the microphone is dependent on the distance of the sound source and the acoustic environment. In active environments, noise is always defined as unwanted sound compared to wanted sound in certain conditions, as it obscures the wanted signal. When we record speech or music, noise control design is always to be considered. After considering the distance and the environment of the main sound source, sensitivity adjustment is required to control the desirable signals. Moderate sensitivity is preferred although high sensitivity is usually chosen for a sensor; a compromise is achieved as too high sensitivity will amplify noise signals as well as the wanted voice signals.

After the converted voltage is supplied to the LEDs, the lighting intensity of the single coloured LED can be dynamically and automatically changed by the voice control circuit. For example, the high loudness induces brightest light and vice versa. LED goes off when the sound disappears. The same program will also work with RGB LEDs but for colour changing performance. In this sound control circuit which can generate different colours, various switching modes have also been designed, like on and off modes, as well as dynamic and static modes.

Representing information

This bespoke microcontroller program design is based on the change of the white LEDs' luminous intensities and the additive colour mixing of the RGB LEDs. Unlike subtractive mixtures of paints, the additive colour wheel is built with additive primary colours as; red, green and blue, and secondary colours as; cyan, magenta and yellow, which are mixed by two primaries. Following the colour principle, the mixing by three primaries will produce white light. These effects are displayed through the electroluminescent fabric with the dynamic changes of colour vision triggered by variations of the audio environment.

With the ability of expressing mood states, colour changing will act in unison with sound changing to create real smart ambience with dynamic and automatic lighting modes in the smart clothing system. Finally the clothing can detect the wearer's mood by sensing their voice and actuate the change of their mood by changing the colour of the fibre optic garment. In our prototype, two sound and colour matching plans are designed, researched and implemented, as discussed in Chapters 4 and 7.

CHAPTER 4 – CLOTHING DESIGN AND GARMENT MAKING UP

Design research starts from the initial idea to a set of procedures and practical implementation to the final clothes, as shown in Figure 4.1.

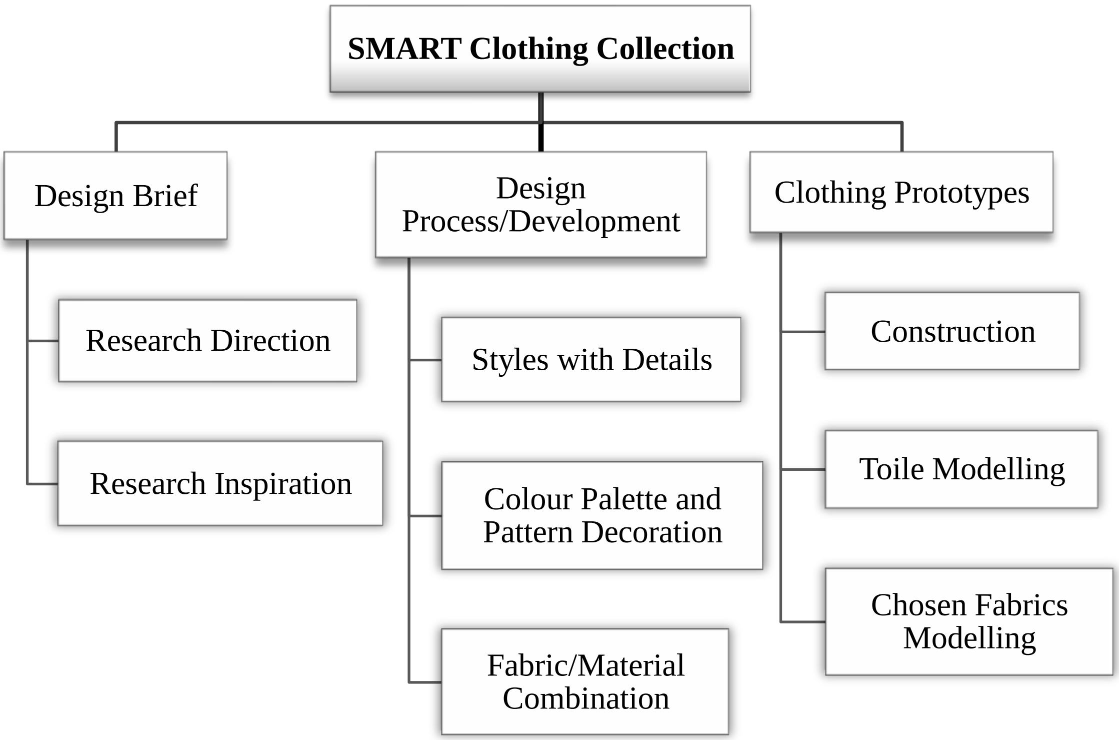


Figure 4.1 Flow chart of the SMART clothing design statement

4.1 Design Brief

The project aim is to create fashionable SMART clothing with integration of electronic and information technologies. The intelligent clothing/fashion/couture as a carrier of the SMART system, should build a very intimate relationship of interacting between human and device. Design includes aesthetics as well as function is shown in both the process and the working of the final clothes. Herein, the function is not only the conventional requirements for wearing the clothing, but also the novel smart functionalities as discussed previously. With these goals, designing of this system has been carried out by considerable research, creative thinking, practical studies, interactive adjustment and design refinement [65].

These goals are established by investigating smart clothing and wearable technology in synergy with fabrics, patterns, garments, fashion and accessories. It means that the creative aspects of this project have not been compromised and in fact the aesthetics underpin all design elements of innovative electronic and information technologies.

Optimum design of two suits, one for a lady and another for a man, are being researched to achieve the best performance for both aesthetics and functionality.

4.1.1 Research direction

As already stated, the design research direction is the interface between contemporary fashion and technology. This new area is defined as "Supermodern [66]" techno-fashion for the contemporary urban metropolis. To pursue aesthetic design, the basic fashion design principles are re-evaluated. Taking into account the clothing wearing properties, high technological functions are carefully integrated by highly specialised couture sewing techniques, which are best suited with the delicate and sophisticated miniature electronic and information technologies. This is why the project is stated as — high fashion meets high tech with tailor-made aesthetics and functionality.

<u>Fashion prediction</u>

The evolution of technological clothing has been long and has had a massive impact since the 1960s, when high-performance materials and design techniques fused in the development of the spacesuit [67]. Those revolutions transformed the way humans perceive themselves and anticipate the future. Lifestyle has gained more recognition between human and environment in the mastering of clothing. Many couturiers and designers have projected their works into the future as avant-garde, smart, progressive and super modern. Techno fashion is designed to respond to the physical and psychological changes by smart materials and technologies.

To detect, measure and decode the mood of the wearer by a garment, this project is coded as "*Power the Mode, Light the Mood*", creating a kind of talking garment. It consists of outerwear and innerwear coordinated garments as a suit with the chic and tailored look. The luminescent innerwear is lit by photovoltaic outerwear to make the entire outfit working as in synergy and as an energy efficient and intelligent mood changing system.

<u>Market analysis</u>

Broadly speaking, new technology trends have influenced all markets from mass products for casual and every-day wear, to sports, medical and military, as well as the tailor-made haute couture. Clothing as an essential component of everyday life, allows technologies to engage with the human body in a functional manner. Fashion allows these technologies to perform not only in a functional manner, but also in an aesthetic form with cultural and social influences [20]. Nowadays, technology is merged with fashion and it is becoming increasingly more accepted by wearers. The highest interpretation of this aesthetic form is haute couture, from which the clothes are made for specific customers, from extraordinary fabrics and sewn with extreme attention to detail [68].

One of the aims of this project is to target smart couture as sketched in Figure 4.2. Based on wearable technologies and developing intelligent clothing, smart couture is practical as well as aesthetic, for the young and ambitious groups of the population – for both ladies and men who are familiar with the idea of fashion and technology.

Figure 4.2 Smart couture – "*Power the Mode, Light the Mood*"

4.1.2 Research inspiration

The technological concept of this project is to present a smart clothing system capable of mood changing through audio signal conversion technology, powered by energy harvesting based photovoltaic subsystem through wearable electronic technology. In addition, this energy harvesting subsystem is also capable to power portable electronic devices, such as mobile phones and PDAs. The design goal is to make those technologies wearable, beautiful, fashionable and sustainable in a collection consisting of two suits, one for a lady and another for a man. Therefore, the design inspirations are triggered by fashion technology along with the inner psyche of the art.

<u>Sources of inspiration to create ideas</u>

Where do the ideas of design come from? Conceptually and technologically, this design research starts from the mind wanting to build an intelligent system which includes non-textile materials such as solar panels, integrated circuitry, battery, LEDs, fibre optics and the like. The images of these objects appear in unusual forms which seem far from clothing or fashion design, but closely interact with human beings and are becoming part of ongoing trends. Therefore, ideas can come from anywhere without any limitation for imagination. The question on how modern technology could blend with clothing and fashion is answered in this project.

As far as ideas are concerned, past experiences and impressions stored in our subconscious inspire personal association of ideas [69]. Although engineering products and electronics become more flexible and smaller, they leave different impressions and experiences to textile based designers who are used to conventional artistic matters like the pleasant and colourful textiles that are very familiar with. Our thinking needs to be encouraged to look forward for designs through new materials that may even need to couple hardness with softness, with textures and colours in both subtractive and additive mixing.

Origami is one inspiration to interpret the feature of changing the forms of an object. As the art of paper folding by geometrical shapes and manipulations, origami transforms plain material into three-dimensional form through folding and sculpting techniques, as shown in Figure 4.3. This art form enables many creations to be made in different design realms of new shapes, new constructions, new packaging and new modes, for example in paper folding art as shown in Figure 4.4 and fabric folding art as shown in Figure 4.5.

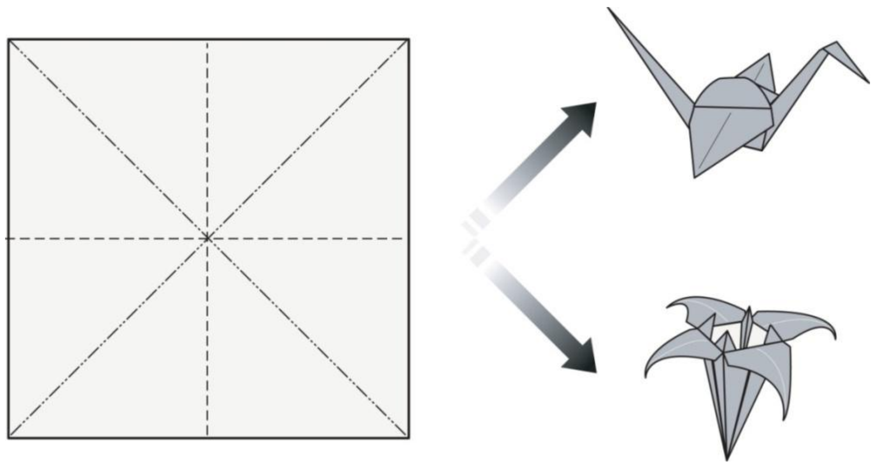


Figure 4.3 Plain paper transformed to three-dimensional features by Origami

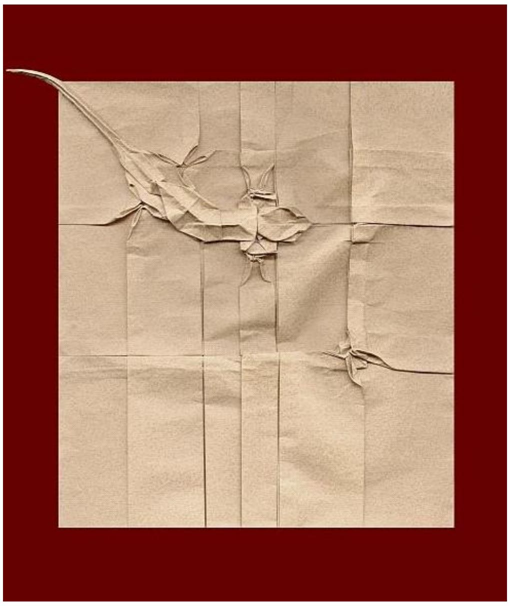


Figure 4.4 Paper folding art

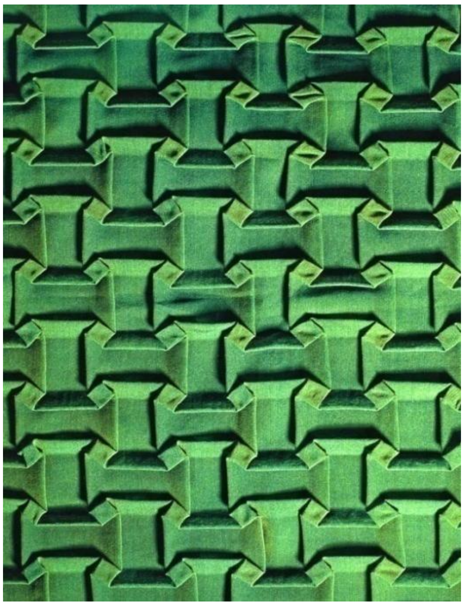
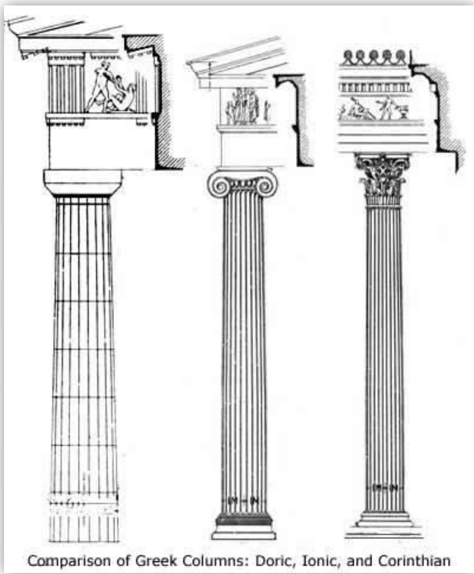


Figure 4.5 Fabric folding art

Another inspiration is the intuitive association between the spectrums of fashion and architecture. Both have to share the functions of providing the body with shelter and protection, as well as to create three-dimensional space and volume from two-dimensional materials. Although fashion and architecture concern human enveloping in a different scale and manner, their functional technology and aesthetic styling are developing with the spirit of our time. The connection between clothing/fashion and building/architecture are so intriguing that similar aesthetic strategies can create buildings fluidly and make clothing architectonically [70]. Figures 4.6 and 4.7 show the design rhythm in ancient Greek columns and Chinese roofing, while Figures 4.8 and 4.9 display the similar elements applied in traditional kilt and fashionable dress.



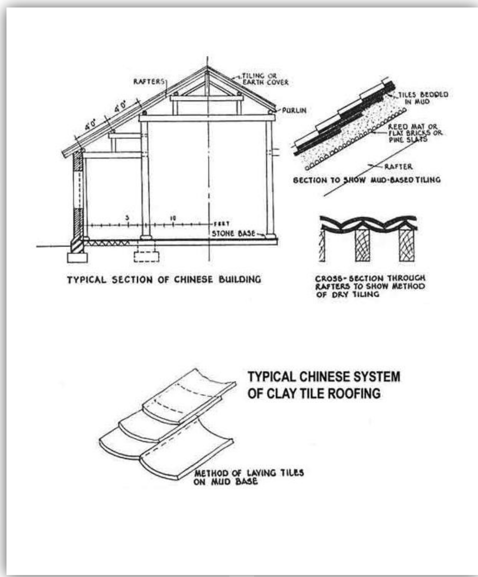


Figure 4.6 Design of ancient Greek columns

Figure 4.7 Design of ancient Chinese roof

Figure 4.8 Pleating deign in traditional kilt

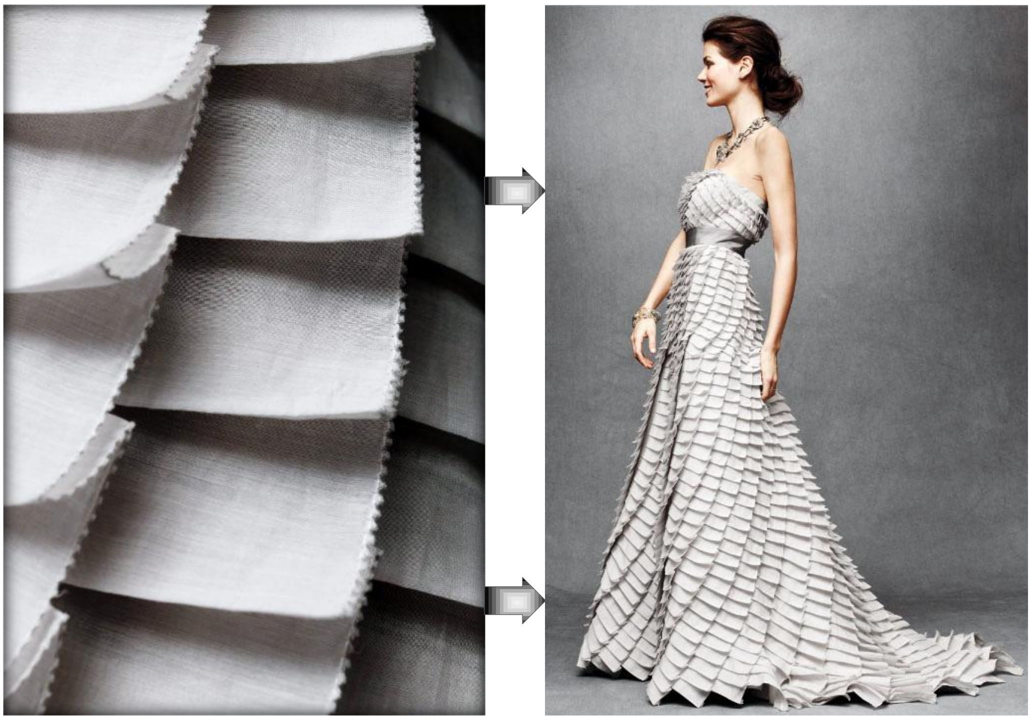


Figure 4.9 Folding and layering design in fashionable dress (Courtesy of BHLDN)

As far as colour is concerned, its physical and psychological factors further inspire the innovative part of the research conception, which is also discussed in Chapter 3. Light, as the source of colour, is delivered in an optical way in which colours might be mixed and changed. But our environment is perceived by us not only in the visual format, but also through hearing. For instance, we feel unbearable noise the same as we see the colour in disorder. This encourages the experience of sound and vision to be altered: reduced/change or increase/change as will be discussed later. Instead of just be aware of our environment, the interpretations of this concept also involve the ability to express our feelings and to examine the problems in a more intuitive manner [69]. Figures 4.10 – 4.12 show how analogies of colour, music and mood can be perceived in a circle, called the chromatic circle.

Figure 4.10 Newton's colour circle

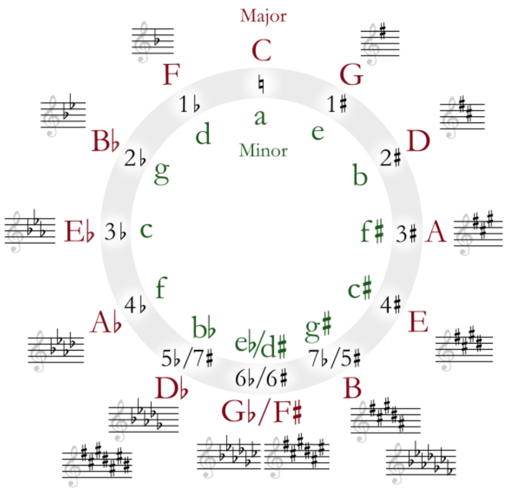


Figure 4.11 Circle of fifths

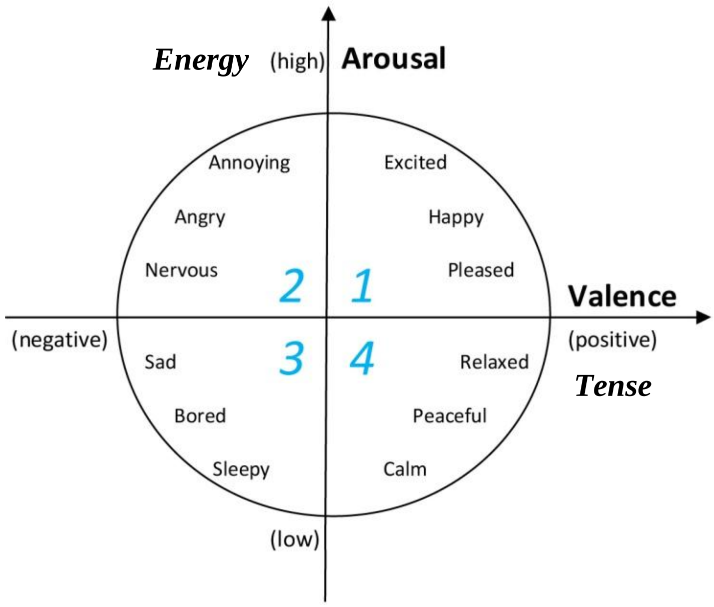


Figure 4.12 Thayer's arousal-valence emotion plane [59]

Personal experiences indicate the individual sense of feeling, taste of beauty, and understanding of an object. They are original sources of inspiration to an idea. Mostly, new ideas are also influenced and developed through a response to external stimuli, as in the work of other designers in the same field, or in entirely different realms [69]. Every designer, who is engaged in a visually creative activity, will build up a valuable library of ideas via different activities like reading books and magazines, drawing pictures, shooting photographs, and so forth. Since nothing ever happens in isolation, the personal inspiration could be extended profoundly through external resources.

Paper folding art; one of the main personal inspiration for the conceptual design of the clothing in this project, can be represented by fabrics and other flexible materials. The use of geometry to generate form is shared in furniture, architecture and clothing design, as shown in Figures 4.13 – 4.15.

Figure 4.13 Paper folding art in furniture design

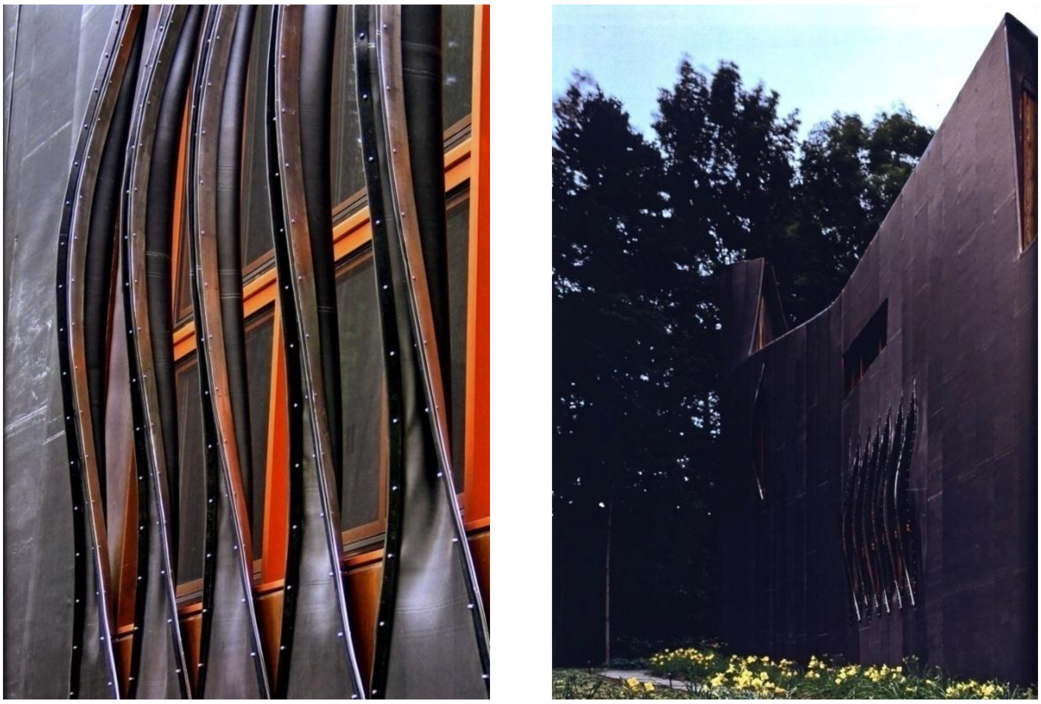


Figure 4.14 Paper folding art in architecture design

Figure 4.15 Paper folding art in clothing design

The advances of materials and information technologies push the boundaries even further. For example, photovoltaic and luminescent technologies are not only increasingly used in the design of interior and exterior buildings, as the examples shown in Figures 4.16 and 4.17, but also realized for the SMART clothing system researched in this project.

Figure 4.16 Rachel Wingfield and Mathias Gmachl, 'Digital Dawn' – A light reactive window blind inspired by photosynthesis and conceived with solar powered textile, 2004 [71]

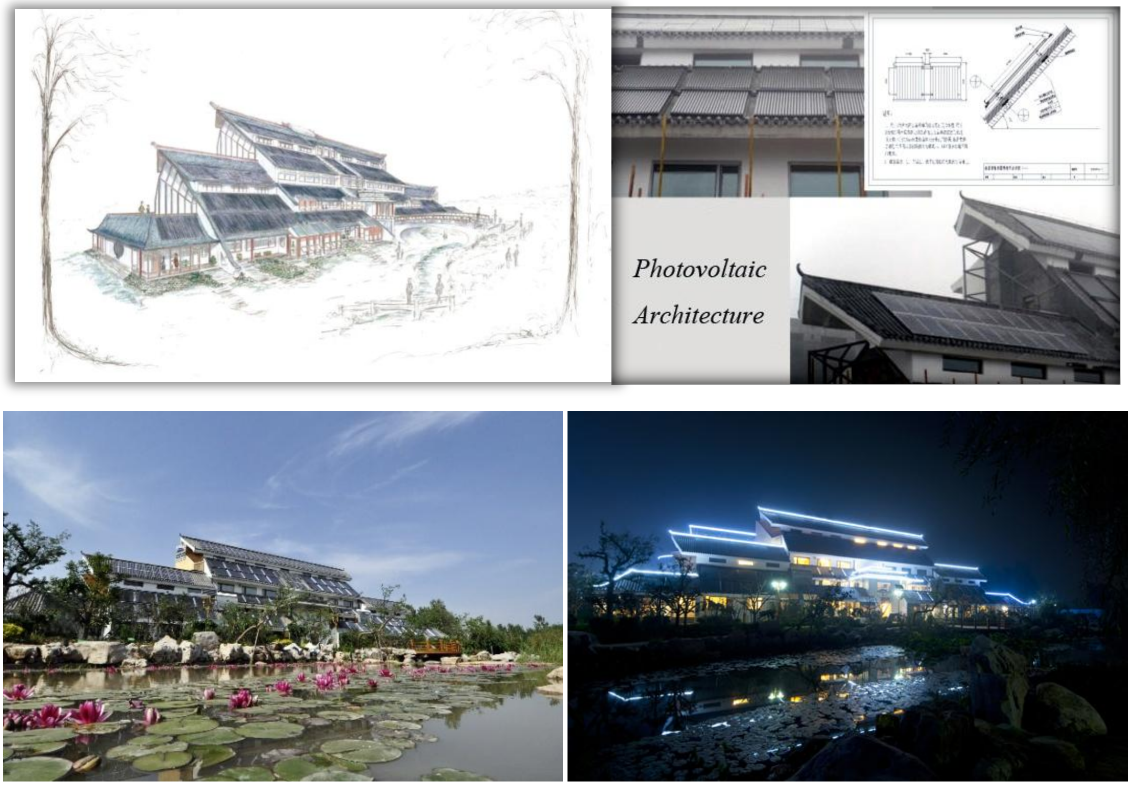


Figure 4.17 Douglas Wilk, 'Time and Space' – A zero emission house of solar powered water-heating-illumination systems, 2010 [72] [73]

Extraordinarily, the knowledge of optical mixing brings us to another way of understanding and designing colours. With the synergism of electronics and information technologies, colour design can be performed dynamically in real time and can be also intelligently controlled. Figure 4.18 displays controlled RGB LED lighting design by amBIENT partnered with Architainment Ltd and Firefly Automation to provide everything from a subtle ambience to dynamic entertainment lighting to suit a wide range of occasions [74]. Another interior application of innovative luminous fabrics is shown in Figure 4.19.

Figure 4.18 amBX-powered lighting system [74]

Figure 4.19 LumiGram curtains in different colour lighting [75]

Development of an idea

The work of creating ideas is like collecting inspiration sources and research materials to provide a focus for our thoughts. Nevertheless, ideas usually don't materialize in the ready-made form, but make a long path by gathering substances from many different sources. They provide visual experiences and sensing for achieving the context, developing the vital details and guiding the final design.

The first stage of developing an idea is to draw out the images from inspiration sources with basic elements. *Line* plays fundamental role in almost every design, whether in architecture, sculpture, painting or fashion. For example, the imaging of pleats or folds on fabrics has similarity with the folding of origami. *Shape*, to some extent as a connection of lines, can be formed freely or constructed geometrically. *Form* could be considered as a three-dimensional development of shape in terms of its mass and volume [76]. Rhythmic and balanced contrasts are the main theme in the design of this project through combination and construction of different lines, shapes and forms. Many structural experiments have been taken place along this theme before the final design development of the clothing silhouettes, for example as the early developmental and exploratory sketches seen in Figure 4.20.

Figure 4.20 Sketches of structural context

Structural context is only one fundamental part of designing clothing; qualities of *pattern*, *texture* and *colour* affect the final appearance of a garment. Pattern and texture are used to enrich the surfaces, exploring and creating our environment for the visual and tactile senses. More than a mere physically visual effect, colour plays a vital role for personal preferences and psychology [76]. With regard to these three facets, fabric or non-fabric materials are the important interface for translating two-dimensional design into three-dimensional clothing. Material assemblage with harmony may form a bridge between the elements of a design and the development of ideas. Figures 4.21 and 4.22 show these features of traditional tartan and innovative luminescent fabrics materialized in swatches.

Figure 4.21 Traditional tartan fabric swatches – Chromatic and achromatic colours

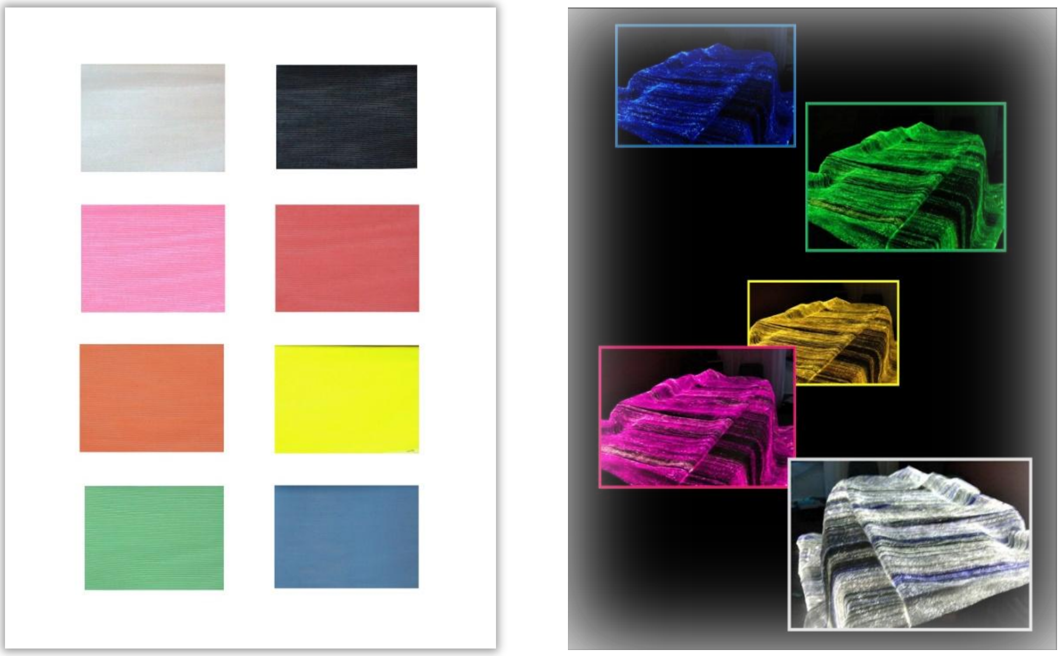


Figure 4.22 Innovative luminescent fabric swatches – Subtractive and additive colours

Once shapes and forms, colours and materials are created by following the inspiration, their details are then being considered. Although it seems to be a small part of the whole clothing design, the level of fashion of the conceived clothing to tailored couture is importantly determined at this stage. Details include everything from collars, cuffs, openings, pockets, fastenings and ornaments, to blinding, piping, lining and stitching. They are not only decorations to form a genre, but they also follow the aesthetic credo "form follows function" [77], as examples shown in Figure 4.23.

Figure 4.23 Sketches of attention to details

4.2 Design Process/Development

Clothing, as a three-dimensional outcome, needs to be considered in all areas including silhouette, proportion, colour, pattern, texture, fabrication and construction before prototype forming. When designing a collection, it is important to build the silhouette with artistic and architectural thinking, experiment the proportions and fulfil the performance of fabric behaviour. In consequence, the process of SMART clothing design of this project is developed as follows:

4.2.1 Styles with details

As primary aesthetic and symbolic elements, styles have symbolic influences on shaping the image of products in the fashion system. By using the metaphor introduced by sociologists, style is a code composed of countless elements and endless combination like letters being mixed up by the alphabet. These elements and combination has an aesthetic value of the sensory experience, such as elegance, youthfulness, ease of use, etc. [78] [79] [80] After analyzing the fashion market orientation, the styles are developed in this project around the design idea and theme on human figures from shapes to forms. Particular attention is paid to the silhouette, proportion and balance, embodying attention to details.

<u>Silhouette</u>

The first activity is the exploration of designing shapes to form the silhouette. Silhouette has been used to symbolize many artworks in architecture, sculpture, painting, and the like. Herein, it implies the outline of a clothing form to describe the shape of the human body of a particular appearance.

The project starts with the construction of basic jackets and trousers. Clothing silhouettes are transformed using proportional segmentation and varied details in order to achieve the desired shapes. Although this is just the styling stage of the total look, all basic wearing functions like fastening and pockets, also the technological functions such as the installation of solar panels, the circuit board and other portable devices need to be considered. Figures 4.24 and 4.25 show the partial working drawings of jackets/coats and trousers design for womenswear and menswear.

Figure 4.24 Working drawings of jackets and trousers for womenswear

Figure 4.25 Working drawings of jackets/coats and trousers for menswear

The innerwear part of this project is designed by unconventional fabrics, as described in Chapter 3. The construction has been considered with the flexible restriction of the novel fibre optic fabrics. Simple and tailored styles are preferred with careful cutting and shaping designs which are difficult to imagine only by drawing. Therefore, the paper-folding modelling method is considered, developed and applied, as the examples shown in Figure 4.26.

Figure 4.26 Paper-folding models of the innerwear design for womenswear and menswear

<u>Proportionality and balance</u>

Since the purpose of clothing is to serve the human body, only the construction of clothing silhouettes is not comprehensive. Another coherent activity is to reveal the clothing shapes and spaces around the human figures in order to experiment the sense of proportion, which is the relationship between the different garment parts with the whole clothing. A successful design depends on the satisfaction of the eye in terms of a balanced proportion. As for clothing design, the balance comes from the relative volume and scale of the style construction created in the design. This sense could be valued by classical and universal rules to provide garment pieces of pleasing proportions. As seen in Figures 4.27 and 4.28, the successful styles of jackets/coats and trousers are selected from the initial working drawings created and put together to form the outfits on human figures. In line with the outfits, the innerwear shapes are further presented in complement of the whole collection suit, as shown in Figure 4.29. The best proportion, balance and rhythm of the suits in the collection have been evaluated and assembled.

Figure 4. 27 Lady's outfits design on the dynamic human figures

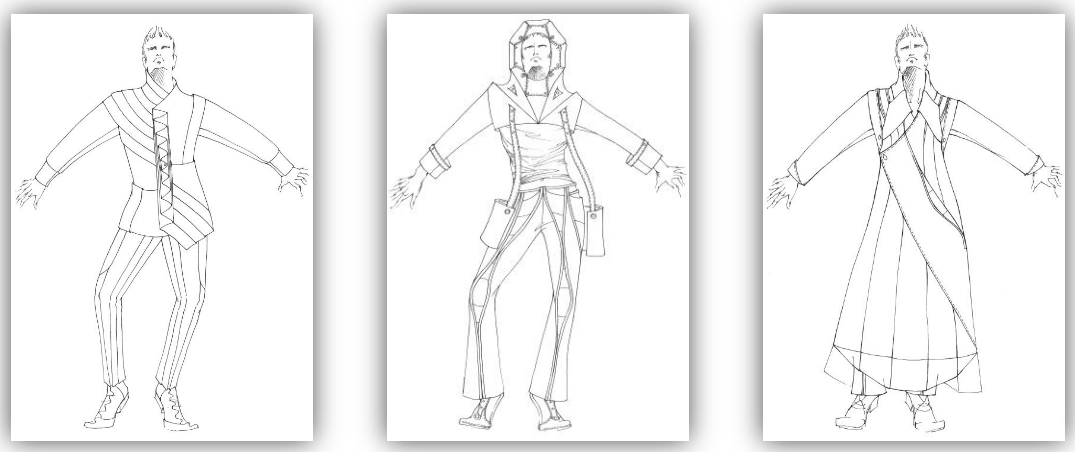


Figure 4.28 Man's outfits design on the dynamic human figures

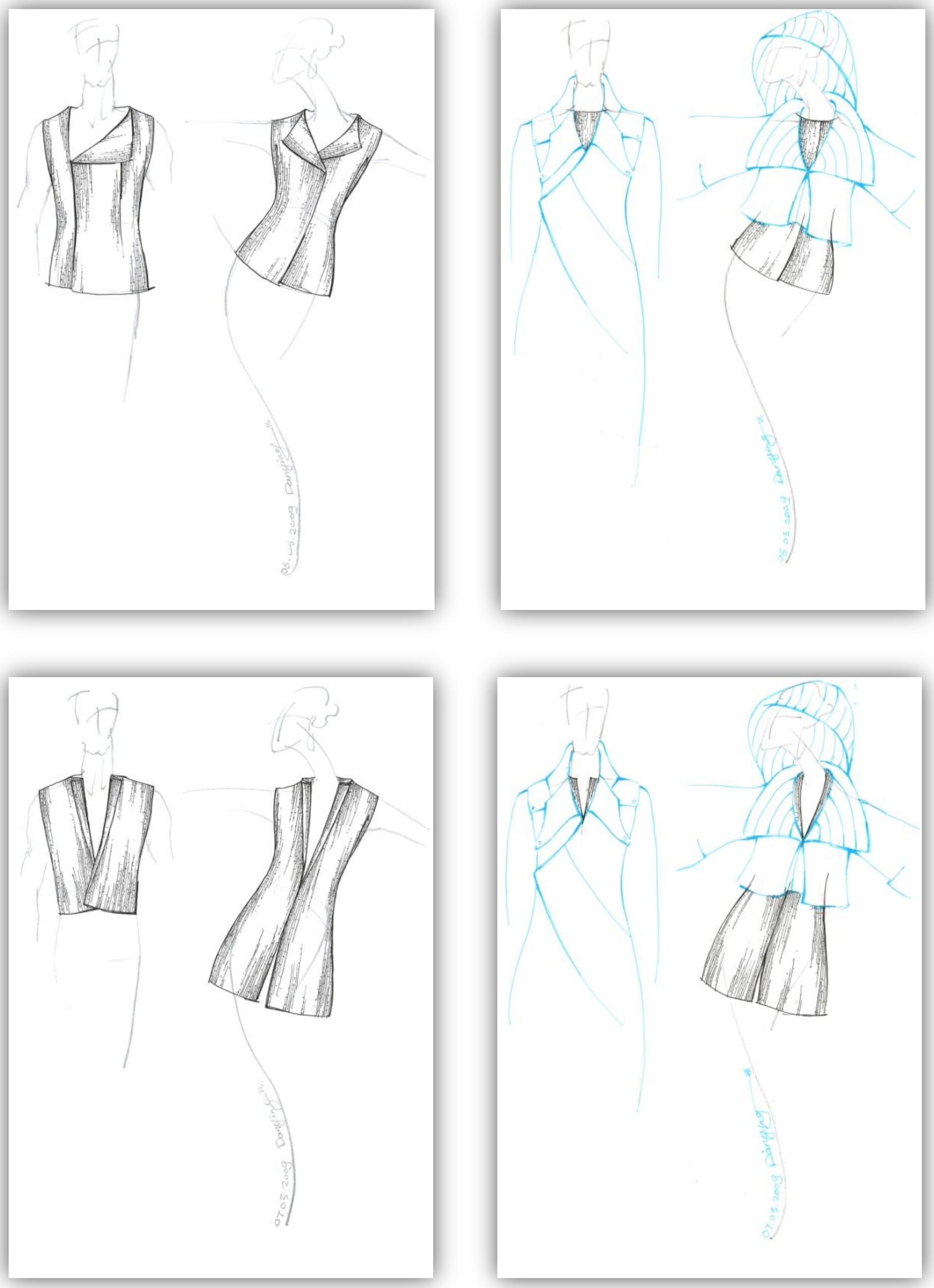


Figure 4.29 Lady's and man's innerwear design presented on the human figures and assorted with the outfits

Generally, the artistic balance is achieved by symmetrical forms of equal distribution from the central impact, also by asymmetrical forms in an unequal volume for different effect. Obviously, more design elements will bring more difficulties to achieve the optimum pleasing and balanced results. Details deliberation of design is necessary for harmonising the clothing silhouette with its wearer. How do the associated elements match a single garment and create the outfit of a collection, and how do the-overall-look relates to the human form, have been examined as observed in the illustrations at different angles; front and back or side views. The preferred suits are chosen as shown in Figures 4.30 – 4.33 with altering details after considerable adjustments and refinements.

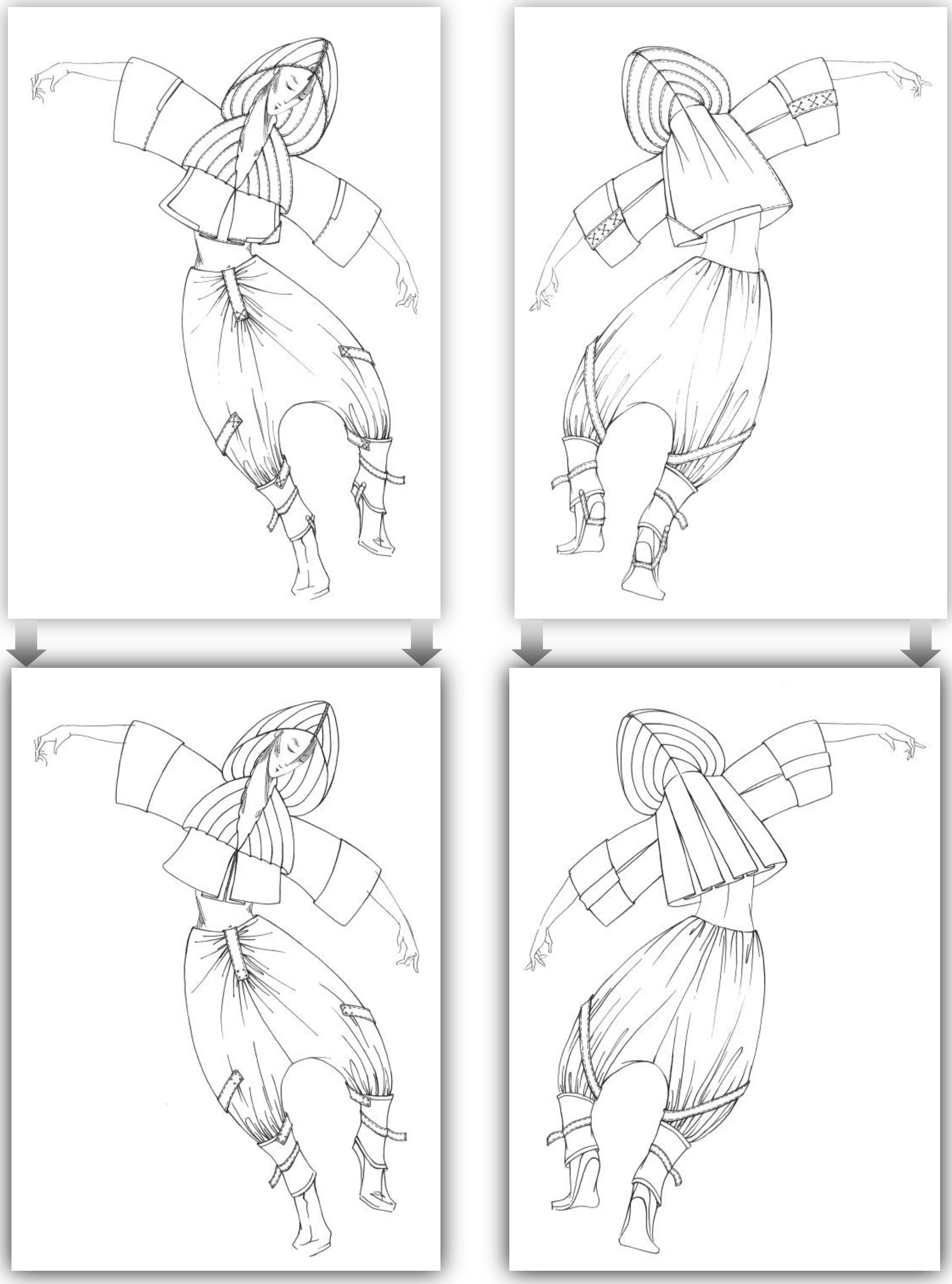


Figure 4.30 Lady's final outfit design with detail refinement – Front and Back

Figure 4.31 Man's final outfit design with detail refinement – Front and Back

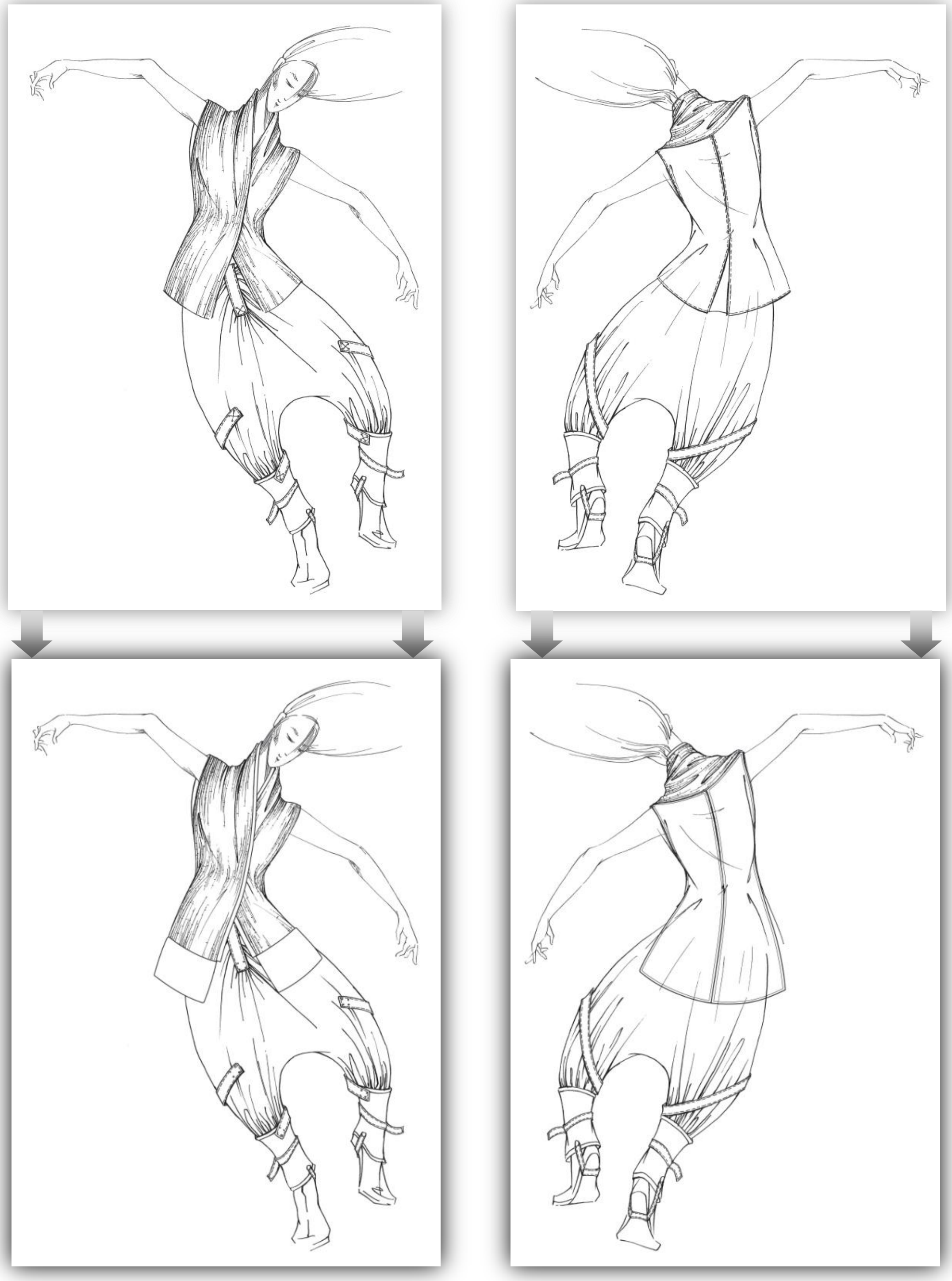


Figure 4.32 Lady's final innerwear design with detail refinement – Front and Back

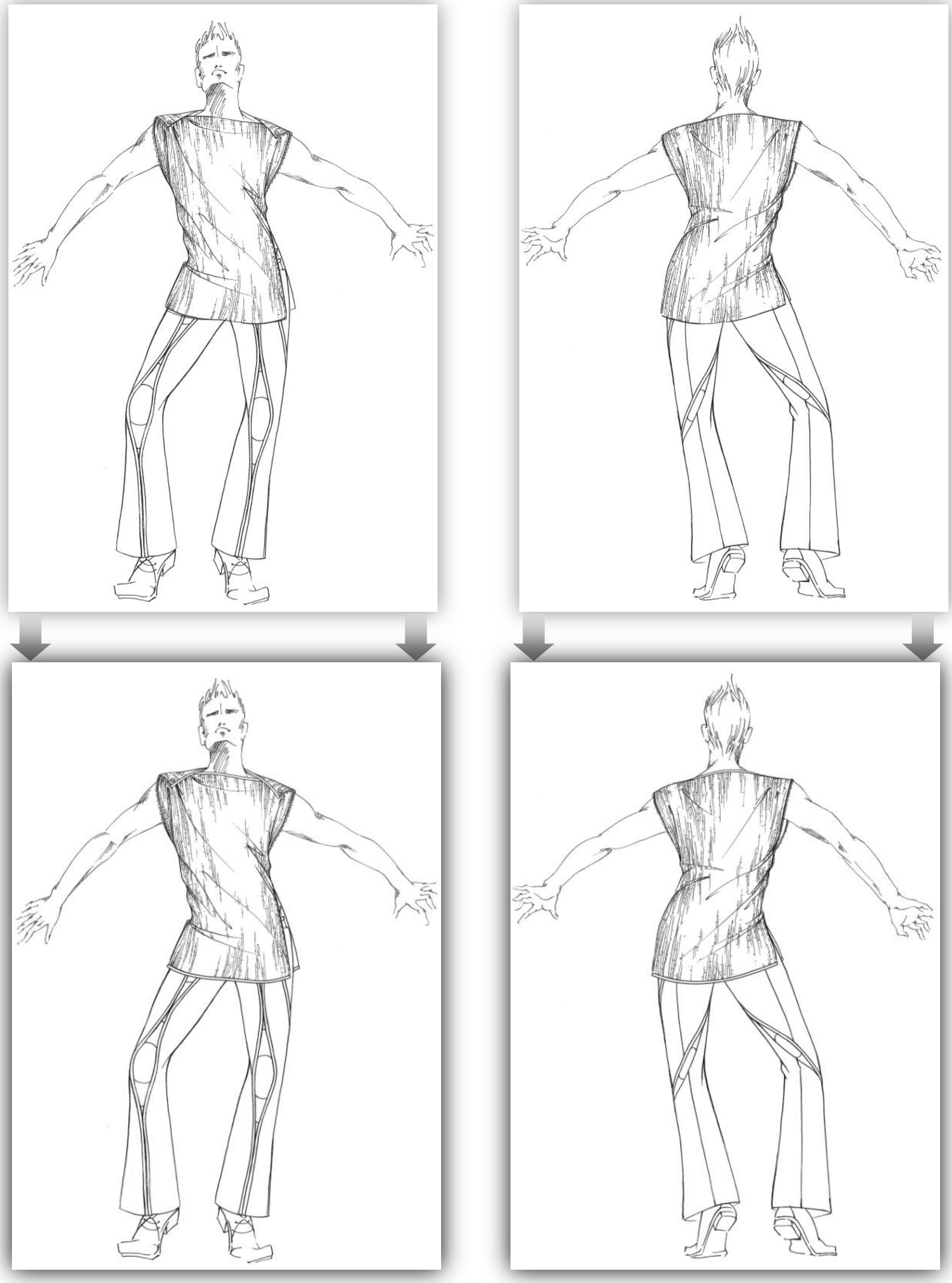


Figure 4.33 Man's final innerwear design with detail refinement – Front and Back

4.2.2 Colour palette and pattern decoration

Silhouette and proportion as presented in the clothing designs are not featureless images. A graphic silhouette could be dramatically different with proportional or contrasting shade fillings, which is known as colour blocking. Basically, colour blocking creates positive and negative effects, which develop the balance and proportion differences in accordance to the rhythm. Typically, the repetition and comparison of the rhythm create more visual impact of patterns. These rhythmic patterns cannot only provide the contrast of colour formation, but also focus attention on or away from the design features, such as the patterned tartan coordinates with solar film panels. Colour design in this project plays a fundamental role in styling silhouette and proportion, as well as indicating the wearer's mood. The outerwear which contains photovoltaic panels is designed with subtractive colours. And the innerwear consisting of LEDs and fibre optics is designed with additive colours.

Colour schemes by subtractive colour theory

Based on the colour theory and the colour wheel, the colour palette in clothing design can be proposed by three schemes; achromatic scheme which is colourless, black, white and grey; monochromatic scheme which is based on shades of the same primary colour; or complementary scheme which combines shades from the opposite segments of the colour wheel [81]. The selection and application of the colour palette can create strong visual impact and harmony. In designing the outfits of womenswear and menswear collection, three colour schemes were experimented as shown in Figures 4.34 – 4.36. The achromatic scheme in Figure 4.36 was preferred to match the black and white grid-patterned solar panels, and grey luminescent fabrics. Although the applied achromatic tone is simple, the squares and lines of the jacket are contrasted with folds and pleats of the trousers to create lively coordinated patterns. The set of large squares and lines in a pattern works in harmony with the black and white grids of the solar panels.

Figure 4.34 Complementary scheme

Figure 4.35 Monochromatic scheme

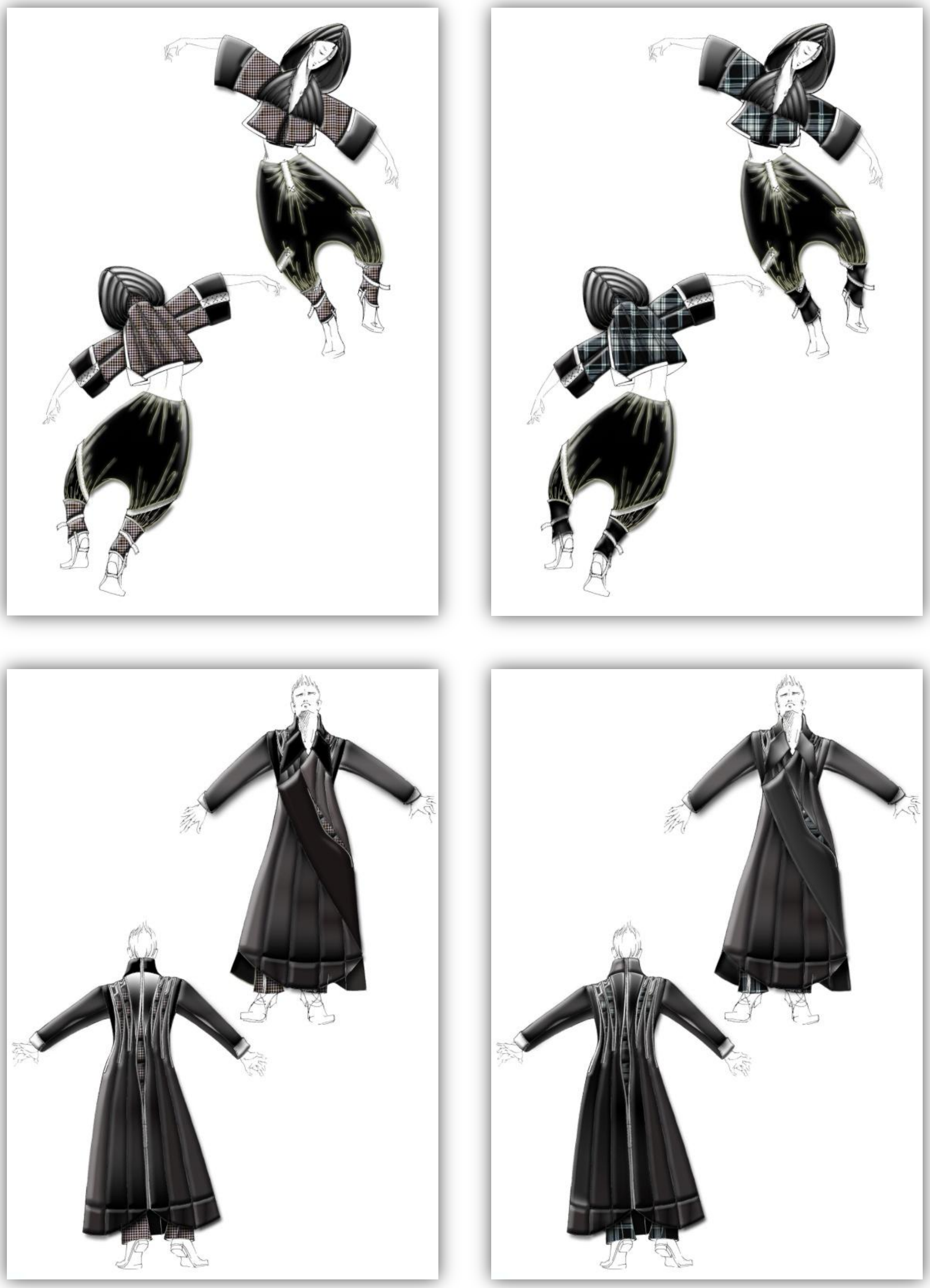


Figure 4.36 Achromatic scheme for the lady's and man's outfits design

<u>Colour changing design by using additive colour theory</u>

One of the big challenges is the innovative colour changing performed by the innerwear. This garment is made up of fabrics which contain LEDs and fibre optics. As shown in Figure 4.37, the innerwear is presented as a grey garment in the daytime, but it changes colours according to the wearer's moods shown in the dark. To be technologically realized, additive colour theory has been used for the RGB LED lighting sources. This colour changing design is investigated and exploited by microcontroller based information technologies which are described in Chapter 3. Diverse RGB design schemes shown in Tables 4.1 and 4.2 are coded in software and can be extended to more colours as shown in Table 4.3 according to research in psychology.

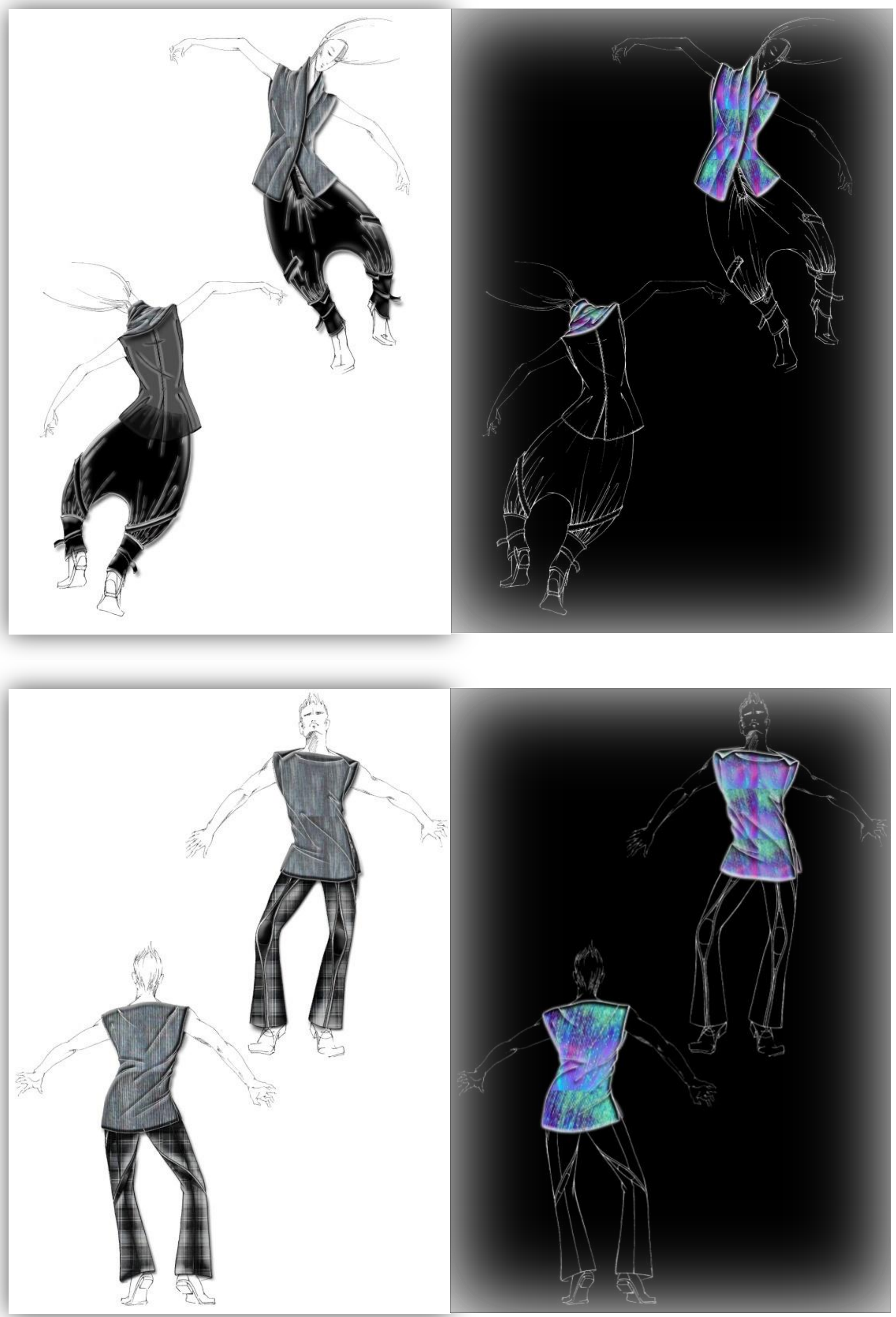


Figure 4.37 Colour schemes for the lady's and man's innerwear design

Sound Volume	Colour Changing			
Halt		Black	0 0 0	#000000
Low		Blue	0 0 255	#0000FF
Moderate		Green	0 255 0	#00FF00
High		Red	255 0 0	#FF0000
Tutti		White	255 255 255	#FFFFFF

Table 4.1 Additive colour system, 5 colours design

Sound Volume	Colour Changing			
Halt		Black	0 0 0	#000000
Low		Blue	0 0 255	#0000FF
Low to Moderate		Cyan	0 255 255	#00FFFF
Moderate		Green	0 255 0	#00FF00
Moderate to High		Yellow	255 255 0	#FFFF00
High		Red	255 0 0	#FF0000
High to Low		Magenta	255 0 255	#FF00FF
Tutti		White	255 255 255	#FFFFFF

Table 4.2 Additive colour system, 8 colours design

Sound Volume	Colour Changing			
Halt		Black	0 0 0	#000000
Low		Blue	0 0 255	#0000FF
Low to Moderate1		DeepSkyBlue	0 191 255	#00BFFF
Low to Moderate2		Cyan	0 255 255	#00FFFF
Low to Moderate3		Aquamarine	127 255 212	#7FFFD4
Moderate		Green	0 255 0	#00FF00
Moderate to High1		YellowGreen	154 205 50	#9ACD32
Moderate to High2		Yellow	255 255 0	#FFFF00
Moderate to High3		Orange	255 165 0	#FFA500
High		Red	255 0 0	#FF0000
High to Low1		VioletRed1	255 62 150	#FF3E96
High to Low2		Magenta	255 0 255	#FF00FF
High to Low3		Purple	160 32 240	#A020F0
Tutti		White	255 255 255	#FFFFFF

Table 4.3 Additive colour system, 14 colours design

4.2.3 Fabric/material combination and compatibility

In a fabric, texture is as important as colour and pattern. Colour, pattern and texture are integral to the surface of the fabric and cannot be separated. For example there are many variances of black colour fabrics which caused by texture in terms of different composition, structure or finishing. The final form of the design is realized by fabrics and materials from two-dimensional illustration to three-dimensional clothing. The visual, tactile and structural qualities of the colour, pattern and texture of the fabric, and also the combination of different kinds of fabric and non-fabric materials need to be considered.

Mixture of natural and synthetic fabrics

The actual cutting and draping silhouette of clothing depends on the fabric, while the performance and the behaviour of the fabric are determined by the fibre and yarn composition and on the mechanics of the yarns and fabrics. In order to apply the best suitable fabrics for clothing, it is important to be acquainted with the fabric performance and technology when designing. The fabrics have been chosen to enhance the end-use properties of comfort, fitting, shaping, appearance, quality, versatility, ecology and sustainability. Differences in texture and pattern contrasts, such as hard and soft, coarse and smooth, solid and fluid, cool and warm may be found.

In womenswear, a fine woollen tartan is chosen for the jacket design. Silk is used in designing the trousers, and polyvinyl chloride (PVC) fabric is chosen for the hood of the jacket, in which the weather-proof function is needed for solar panel installation. Also the PVC and silk fabric/materials have been designed and used as belt decorations for the trousers. Three types of fabric are shown in Figure 4.38 for providing gradual texture effect, and for enhancing the depth of the colour tone in a series of styling shapes.

Figure 4.38 Mixture of tartan, silk and PVC fabrics in the lady's jacket design

For the menswear, heavily textured wax cotton fabric and soft cotton lining fabric are chosen for a simple long coat design, as shown in Figure 4.39. Impregnated with a paraffin based wax, the oily property of the cotton is providing a waterproof function which has been used for centuries. Waxed cotton does not only provide a weather-proof function like the PVC coating for installing the solar panels, but also provides a moderate sheen appearance with a crispy handle.

Figure 4.39 Black waxed cotton fabrics for the man's coat design

Interface between traditional fabrics, technical fabrics and smart non-fabric materials

Fabrics are becoming more “innovative” and even “smarter” to echo advances in other technologies, such as fabrics that change colours in response to heat, light, chemical reactions or electrical current. In this project, smart technologies have been developed and integrated with new designs of clothing. No matter how effective these innovative technologies are, the design needs to be simple, smooth and incorporating traditional fabrics, technical fabrics and non-fabric materials in the clothing.

Solar panels are the first part of this smart technology system. The bridge for linking between panels and fabrics is crucial. For electricity considerations, electrodes of solar panels are necessary to be protected by weatherproof fabrics. Therefore, thin Gore-Tex fabrics with thermo bonding property are used to insulate the electrodes and conductive materials. PVC coated fabrics and waxed cotton fabrics are individually combined with Gore-Tex packaging to coordinate with the overall look of the lady’s jacket and the man’s coat, as shown in Figure 4.40.

Figure 4.40 Using Gore-Tex fabrics as the linkage between tartan/waxed cotton fabrics and film-like solar panels

Another smart part of this clothing system is the luminescent fabric for the innerwear clothing design. According to the woven substrate, silky nylon fibres are intersected together with the fine optical fibres. Although these smart “light weaving” fabrics are made to resemble as close as traditional fabrics, what we wear next to skin and how it might feel needs to be considered. Chiffons are used as a close-fitting layer attached to the lady’s luminescent garment piece, as shown in Figure 4.41; and cotton linings are used for the man’s luminescent garment pieces, as shown in Figure 4.42.

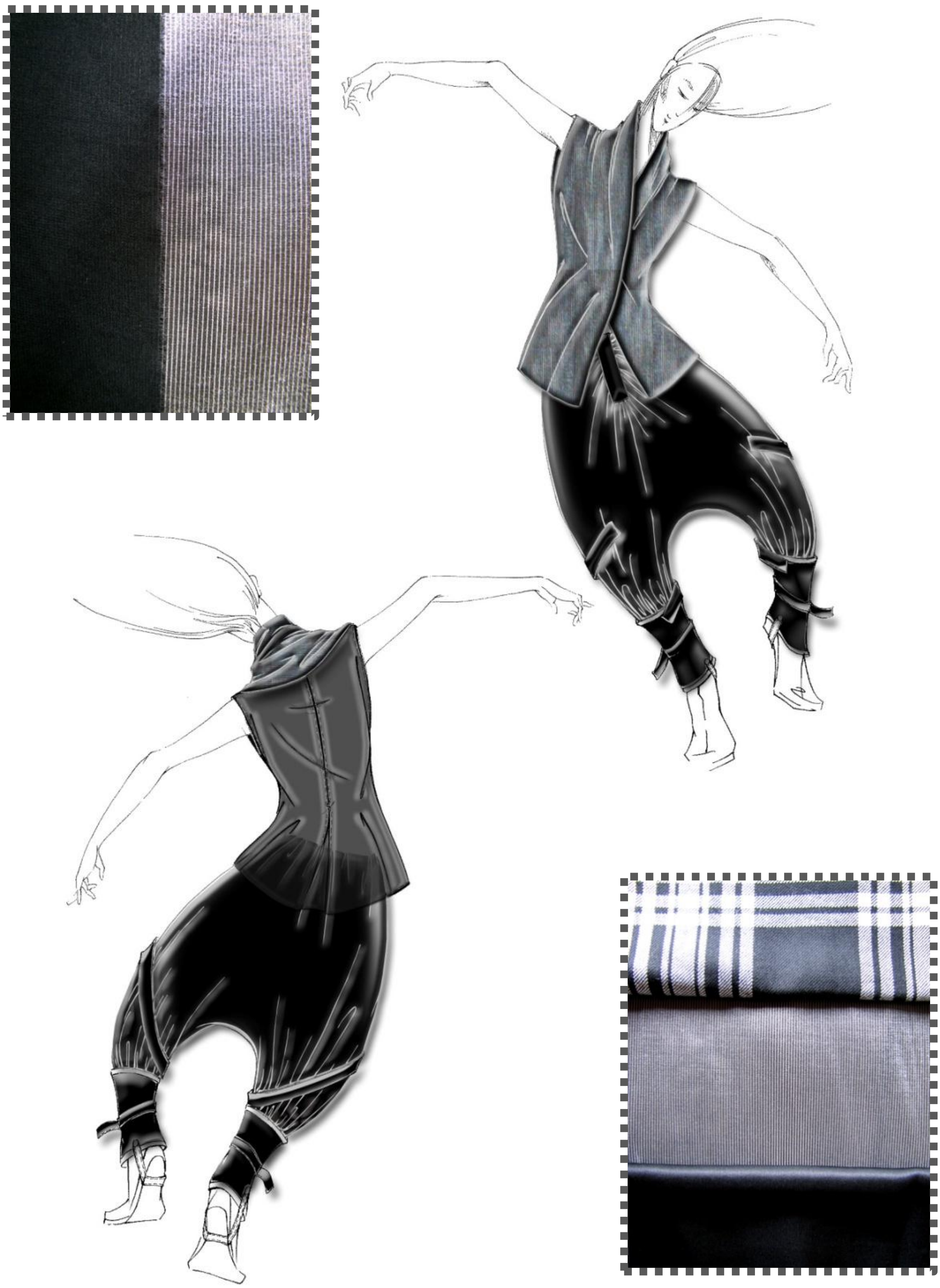


Figure 4.41 Mixture of chiffon and luminescent fabrics in the lady's innerwear design

Figure 4.42 Cotton linings for the man's luminescent innerwear design

Between the traditional fabrics and the non-fabric materials, there occurs the main interface of design and technology which is extremely vital to realise the tailor-made aesthetics and functionality required. Conductive fabric (Figure 4.43), which will be discussed in Chapter 6, is the best alternative to be used in wearable electronics and smart clothing instead of using traditional wire connections. Snap fasteners (Figure 4.43) are considered to be used as the connecting points.

Figure 4.43 Conductive fabrics and snap fasteners

4.3 Clothing Prototypes

After all aesthetic and functional design elements are considered, the next crucial stage is how to practically translate the two-dimensional illustrations to three-dimensional garments. Prototypes for wearer fitting and wearing feeling are essential to realize a successful design. Since there is always uncertainty to whether a new design will actually fulfil what is required, prototypes are important to test the design concept and process. In order to solving any unexpected problems, original ideas and drawings, design alternatives and technology improvements have been investigated. Design research prepares and tests every procedure and technique of making a prototype. Iterative series of prototypes were designed, constructed, tested and tailored for the final clothing collection. Based on the analysis of these prototypes, the final design has been refined and final aesthetic and functional forms emerge after these investigations.

4.3.1 Construction – pattern making and toile modelling

The main task at this stage is how to develop a prototype of the devised clothing design. In order to create the three-dimensional clothing, it is important to consider the human body at first, and then to use skills and intuition to manipulate fabrics around it. A lady's size 12 and a man's size 40 have been chosen for constructing the clothing prototypes of this project. Patternmaking is the practical stage of this process. A garment pattern can be formed by either a two-dimensional or three-dimensional process. Often a combination of methods is used to create the pattern for the optimum appearance and fitting of a garment. [82] Two main methods have been used to accomplish the clothing silhouettes and fit the figure shapes as follows:

Planar cutting

Planar cutting, also known as flat pattern cutting, is a two-dimensional paper drafting method, creating the intended clothing styles from line to shape, and shape to form, based on the body measurements and known pattern calculation [81]. Simplifying the basic patterns as cardboard blocks is the basis of the flat pattern making system. Along with the basic body blocks, outerwear patterns are drafted and cut according to the illustration and working drawings of the clothing design, and by considering seaming of the fabrics. The patterns are then ready to make into samples by calico/toile, and also experimented and evaluated with actual fitting of the samples. In this project, the lady's jacket and the man's coat have been made by this pattern method, as shown in Figures 4.44 and 4.45.

Figure 4.44 Lady's jacket pattern making by the planar cutting method

Figure 4.45 Man's coat pattern making by the planar cutting method

Draping

Alternatively, some garments are constructed not by cardboard blocks but by modelling patterns in calico/toile directly on the mannequin or on a human figure [81]. This three-dimensional method can intuitively obtain a perfect fit by manipulating the exact outline between fabrics and mannequins from draping. Patterns are achieved after marking lines on a calico/toile shell, and transferred from the three-dimensional models to two-dimensional patterns. Draping is especially helpful when developing intricate garment styles or using unusual fabrics [83]. Since the luminescent fabrics have cutting restriction for preserving the maximum light flux, a draping method is used for constructing the innerwear prototypes of the required styling and construction, as shown in Figures 4.46 and 4.47.

Figure 4.46 Lady's innerwear prototype manipulating by the draping method – Front, side and back

Figure 4.47 Man's innerwear prototype manipulating by the draping method – Front, side and back

4.3.2 Form study and toile modelling

After construction, the prototypes are made and fitted on a mannequin or human model by inexpensive and easily draped materials. This type of prototype can provide the basic size, look and feel of the final design without simulating the exact visual appearance and actual function of the final form [84]. In fashion design, calico or toile is used in accordance with the thickness of the chosen fabrics. Without representing the intended colour, pattern and texture or detailed finishing, toile modelling prototypes have used to try the design of garments and the fitting of human figures. The design/technology illustration, working drawings, patterns and samples are also investigated and reconsidered.

<u>Samples for outfit presentation</u>

Since the original design intentions can easily be changed or lost during the prototyping translation stage, considerable sample preparation, development and adjustments are necessary to achieve the optimum result. From outerwear to innerwear, as shown in Figures 4.48 and 4.49, the toile samples are cut from planar patterns or modelled directly from draping. The balance and coordination of the outfits, the fitting and comfort of the wearer, and the ease of body movement are the main considerations for this process.

Figure 4.48 Lady's toile samples fitting – from outerwear to innerwear with front, side and back views

Figure 4.49 Man's toile samples fitting – from outerwear to innerwear with front, side and back views

<u>Electronics arrangement and placement</u>

On the toile samples, the electronic components have been mocked-up with consideration to clothing details and accessories, for example, the layout of the solar panels, the pockets to hold the PCBs, and the connections of the LEDs.

As seen in Figures 4.50 and 4.51, solar modules were arranged in different positions on the upper areas of the lady's jacket and the man's coat. According to power efficiency variance due to wearing and weather conditions changes, the most exposed part of the jacket is the hood and of the coat is the yoke. Hence, these are considered as the most suitable positions.

Figure 4.50 The layout of the solar arrays on the lady's jacket sample

Figure 4.51 The layout of the solar arrays on the man's jacket sample

For the outerwear, several pockets were designed for holding electronic devices, such as the mobile phone, the electronic conditioning and power management PCB. The position and connection of the PCB with the LEDs in the innerwear has been challenging. Figures 4.52 and 4.53 show the concealed pockets with connecting paths embedded between the layers of the garments. The package and connection of the LEDs were designed as shown in Figures 4.54 and 4.55, and are further detailed in Chapter 6.

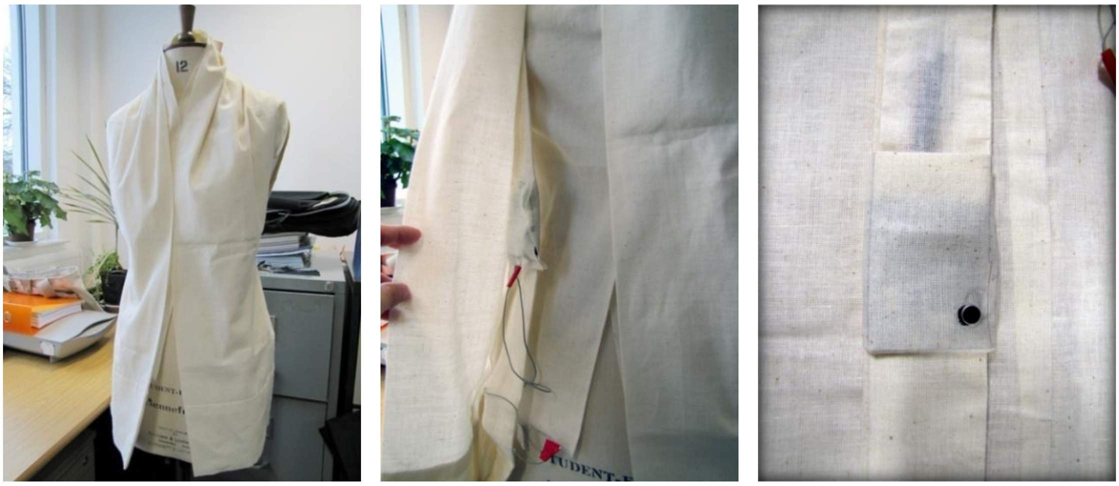


Figure 4.52 Positioning and connecting the PCB in the lady's innerwear sample

Figure 4.53 Positioning and connecting the PCB in the man's innerwear sample

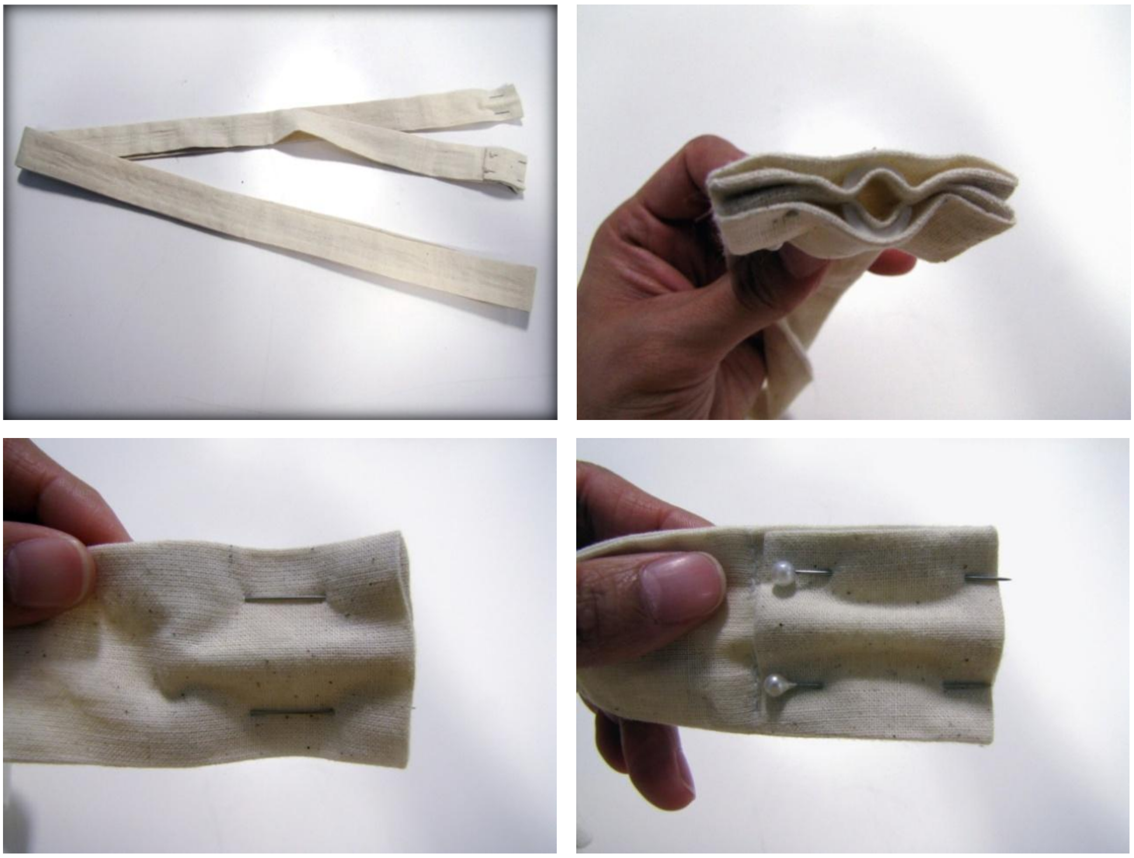


Figure 4.54 LED package and connection with the lady's innerwear garment

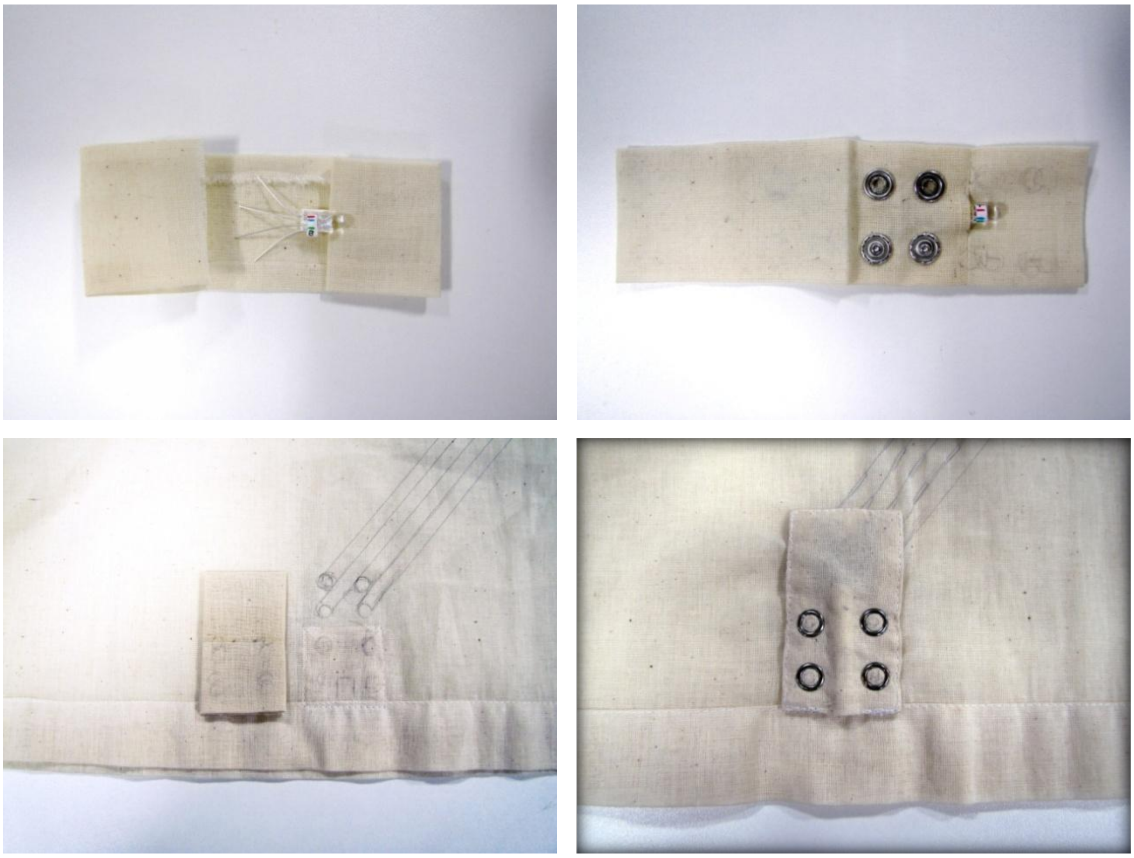


Figure 4.55 LED package and connection with the man's innerwear garment

4.3.3 Functional prototype – Chosen fabrics modelling

The exploration by toile modelling of prototypes has enabled the optimisation of design appearance, garment fitting and wearable technology, focusing at the interface between the wearer and clothing. Consequently, any problems of design or connection and integration between design and technology have been evaluated, before the making up of the real clothing. From the final product point of view, functional prototypes have been created and verified further to consider aesthetics and technological functionalities in the final design. The technical aspects of the implementation are investigated and discussed in Chapter 6. Hereinafter, the smart clothing outfits were made up with haute couture construction techniques.

<u>Assembling and construction</u>

In order to create the final clothing prototypes, cutting, sewing, pressing, interlining, interfacing, assembling and finishing have been performed. Interfacings and interlinings are skilfully attached to the interior of the garments, for aesthetics, shape and support. Attention to detail is considered long before cutting of the fabrics. With the help of the toile samples and by optimum adjustment of patterns, every design is planned elaborately. For example, the patterns of tartan have been placed carefully along with the position of the solar panels and the insertion of the circuitry. A series of photos in Figures 4.56 and 4.57 show the making up process of the assembly of the lady's jacket and of the man's coat.

Figure 4.56 A series of photos to display the assembly of the lady's jacket

Figure 4.57 A series of photos to display the assembly of the man's jacket

<u>Connecting fabrics and non-fabric materials</u>

As stated in Chapter 3, solar panel mounting is crucial for possessing both functional and aesthetic characteristics by combining fabric and non-fabric materials. Fabricated packaging design and embedding techniques have been carried out carefully as discussed in Chapter 6. From the layout design of the toile samples, the arrays of solar panels were particularly considered and have been arranged as a three-dimensional pattern design to blend with the aesthetics of the garment. These optimum aesthetic layout schemes of solar arrays on the lady’s jacket and the man’s coat are shown in Figures 4.58 and 4.59 with front, side and back views.

Figure 4.58 The optimum layout of the solar arrays on the lady's ready-made jacket – Front, side and back

Figure 4.59 The optimum layout of the solar arrays on the man's ready-made coat – Front, side and back

The connections of solar panels, PCBs and mobile phones have been planned to merge with the clothing assembly and construction, as illustrated in Figure 4.60. The detailed implementation of design and technology during the making up process of the garment is presented in Chapter 6.

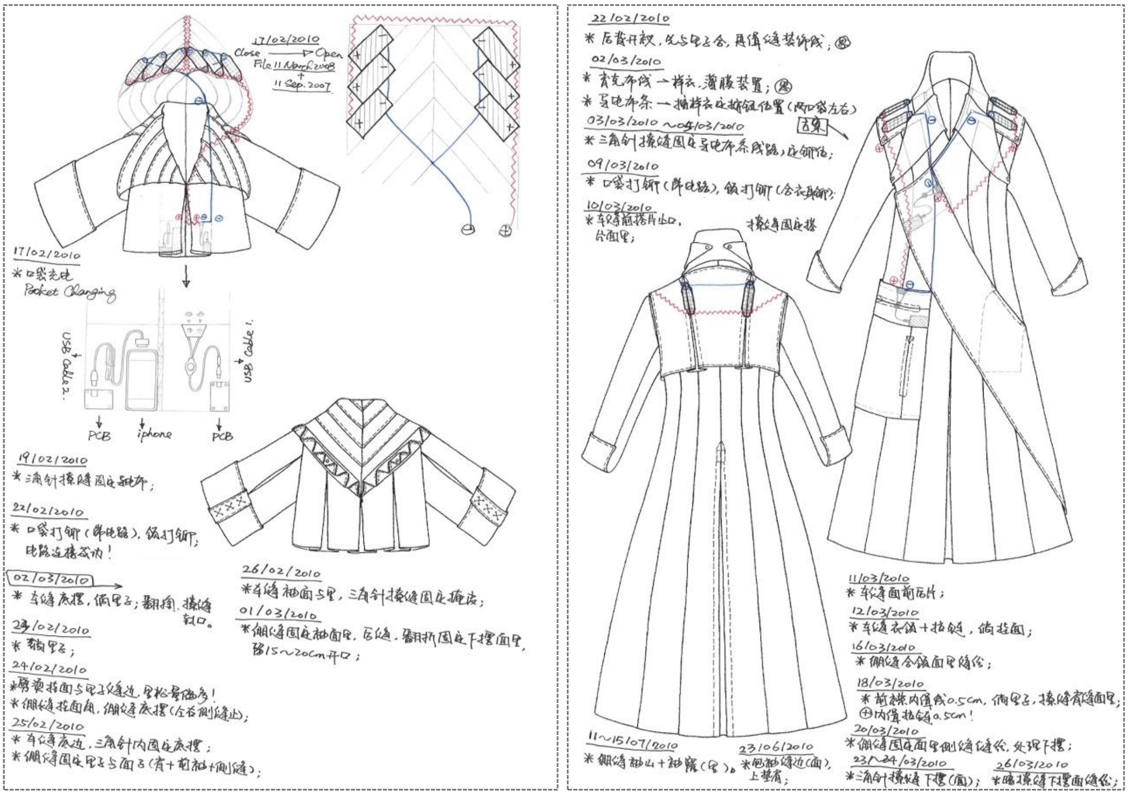
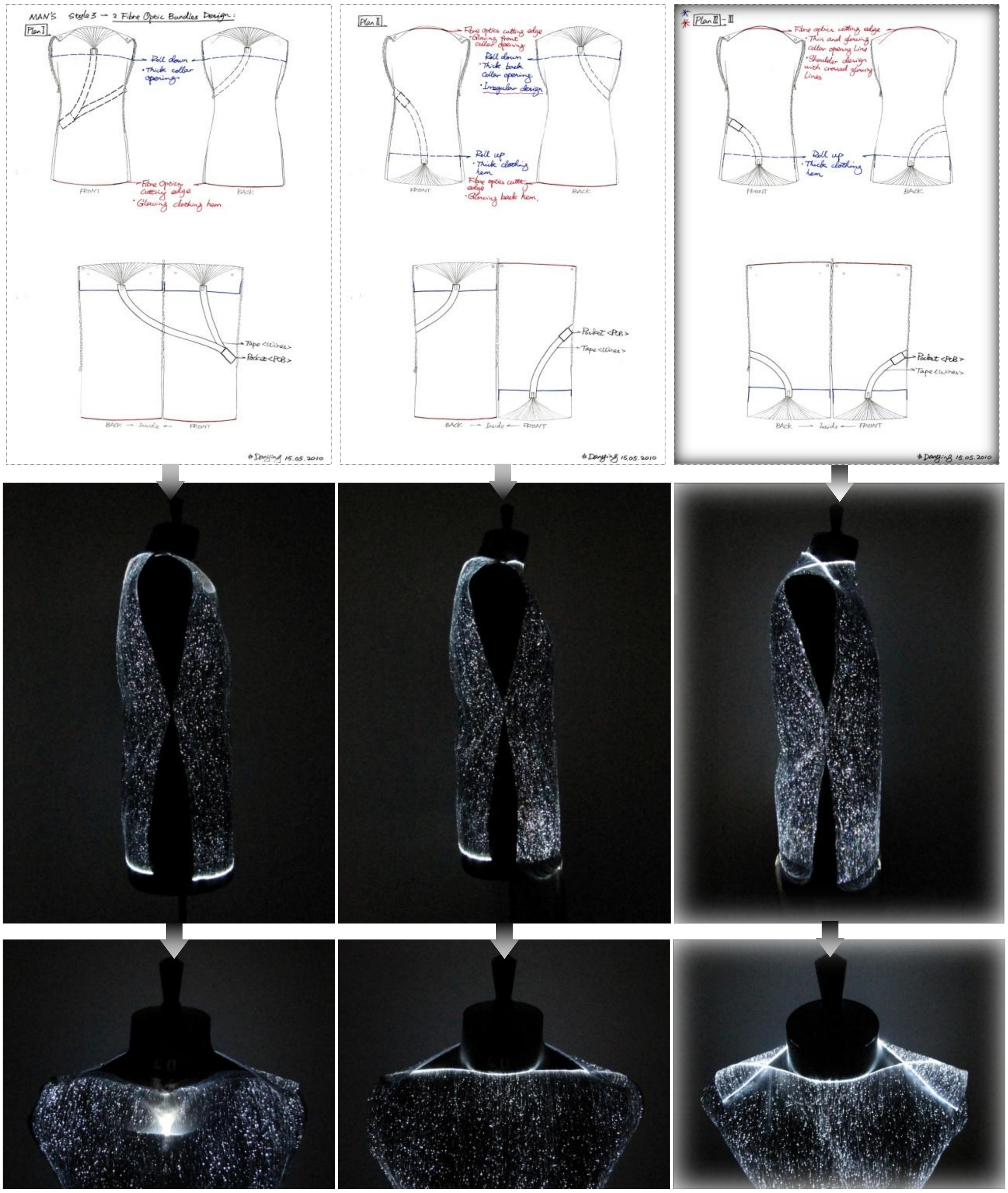


Figure 4.60 Illustrations of the final design for assembling and connecting solar panels with PCB and mobile phone on the lady's jacket and the man's coat

Careful shaping and elegant stitching of the optical fibres and luminescent fabrics can warrant light continuity. Consequently and after careful position experimentation, the most optimum assembly plan was chosen and shown in Figures 4.61 and 4.62 with considerations of seaming, sewing and LEDs connection.

Plan 1 *Plan 2* *Plan 3*

Figure 4.61 Planning the position and connection of the fibre optic bundles in the lady's innerwear garment – the most optimum assembly (plan 3) is highlighted



Plan 1 *Plan 2* *Plan 3*

Figure 4.62 Planning the position and connection of the fibre optic bundles in the man's innerwear garment – the most optimum assembly (plan 3) is highlighted

Along with the assembly construction of different clothing parts, the challenge is continued with the actual interfacing of electronic components, conductive fabric connections and embedded wirings in the fabric and garment. After initial trials of fine wire connections in the lady's innerwear garment, considerable work has been carried out to replace the traditional wires by textile-based circuits and to substitute the conventional solder based connections by snap fasteners, as described in Chapter 6.

From the fashion couture perspective, every facet of the clothing is treated with attention [68]. The finishing of the garment and the connection between fabric and non-fabric materials are carefully made and precisely assembled in some cases by hand stitching. As illustrated in Figures 4.63 – 4.66, the lady’s and man’s innerwear were made up by combining luminescent and traditional fabrics. Every key point was elaborated, redesigned, tested before was made up into the final garments, as shown in Figures 4.63 – 4.66.

Figure 4.63 Illustrations and making up details of the luminescent fabric layer for the lady's innerwear garment

Figure 4.64 Illustrations and making up details of the chiffon fabric layer for the lady's innerwear garment

Figure 4.65 Illustrations and making up details of the man's luminescent innerwear garment with innovative textile-based circuitry

Figure 4.66 Illustrations and details of the man's luminescent innerwear garment with couture making techniques

CHAPTER 5 – WEARABLE ELECTRONIC SYSTEM DESIGN

In a world of complex interconnected systems and dynamically changing environments, the methodology of this project is based on a systems approach [85]. A particular discipline can only address only a narrow aspect of the whole system by fragmented and inadequate knowledge. The separation between designers and technologists causes fragmentation between art and science. The future is integration and working together. This is a philosophy adopted in this project. With technology and design marrying each other, an integrated smart clothing system has been designed, researched and developed. This chapter describes and discusses the developmental stage of the system. Having designed the fabrics and garments with this in mind, in this chapter a more detailed description of the developmental process of the wearable electronics is presented.

5.1 Energy System

The first part of this smart system is the application of solar harvesting technology on the outerwear garment design, as shown in Figure 5.1.

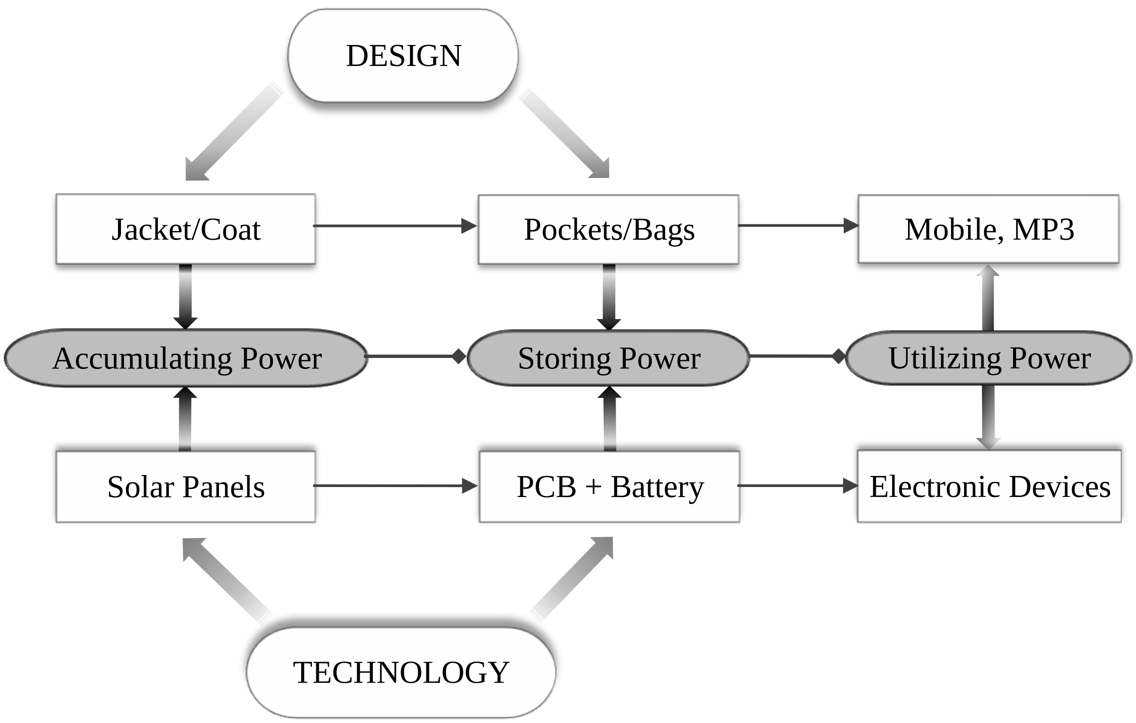


Figure 5.1 The energy system

5.1.1 Solar harvesting technology

For most wearable electronics, supply of power is an important part of system design. With the development of flexible solar technology, harvesting energy by PVs becomes a new way of providing electric power instead of carrying a stationary power supply as in a conventional energy system. In order to be applied on a jacket, a coat, a backpack, or in an accessory, this integrated photovoltaic system has a common layout comprising of solar modules/panels, a power conditioning controller and storage batteries [86]. This energy system is to connect solar panels through a newly designed PCB to a lithium rechargeable battery, so that a charge is provided to electronic devices whatever, whenever and wherever needed. The integration of electronics in the body by clothing is a new technological challenge.

5.1.2 Outerwear design

In the design of wearable technology, miniature and flexible electronic components create innovative variations and functional parameters in clothing [87]. Distribution, installation and transmission are three main challenges. After taking into account the need of maximum exposure to the solar energy, the solar panels are distributed on the upper parts of the lady's jacket and of the man's coat. Interacting with wearable and portable devices, such as mobile phones, MP3s or PDAs, functional pockets and pouches are designed in the outerwear jacket and coat. Energy controlling and storing components are also installed through PCBs in the pockets of the garment. Layering design and make up has played a prominent role by using textile-based conductive fabrics as pathways for connecting the main circuitry.

5.1.3 Smart textile interface

The transmission between each part of the energy system in this project is based on electrical conductivity. In order to integrate electronic components in clothing comfortably and aesthetically, smart textile-based connections and fabric connectors have been developed for adding flexibility and good wearability.

Figures 5.2 and 5.3 illustrate the outerwear prototypes deployed with solar harvesting technology for womenswear and menswear.

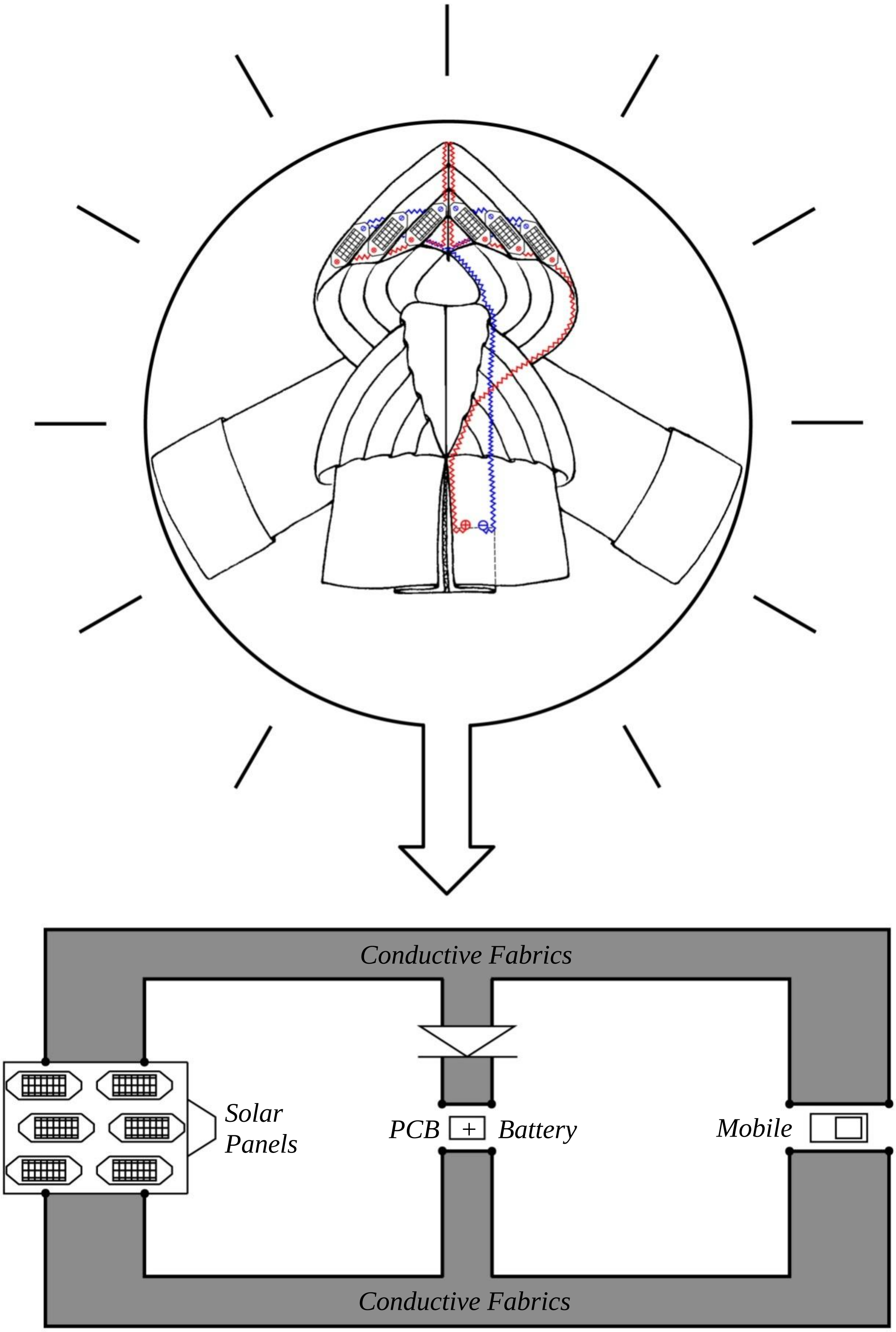


Figure 5.2 Solar harvesting technology and lady's jacket design

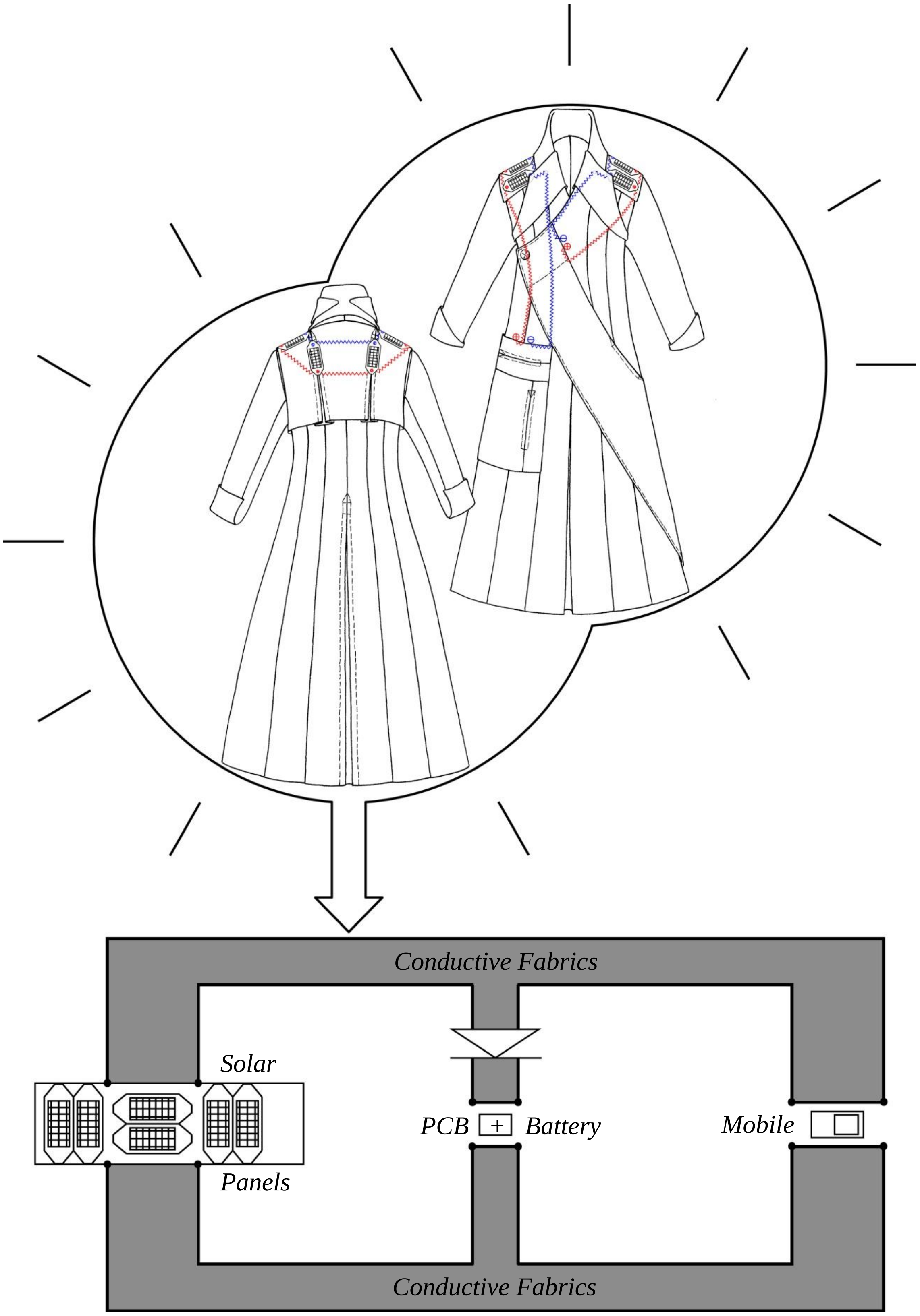


Figure 5.3 Solar harvesting technology and man's coat design

5.2 Information System

On the basis that solar energy can be stored, let us consider the information system. Mood changing technology is applied to the innerwear garment design, as shown in Figure 5.4 and discussed below.

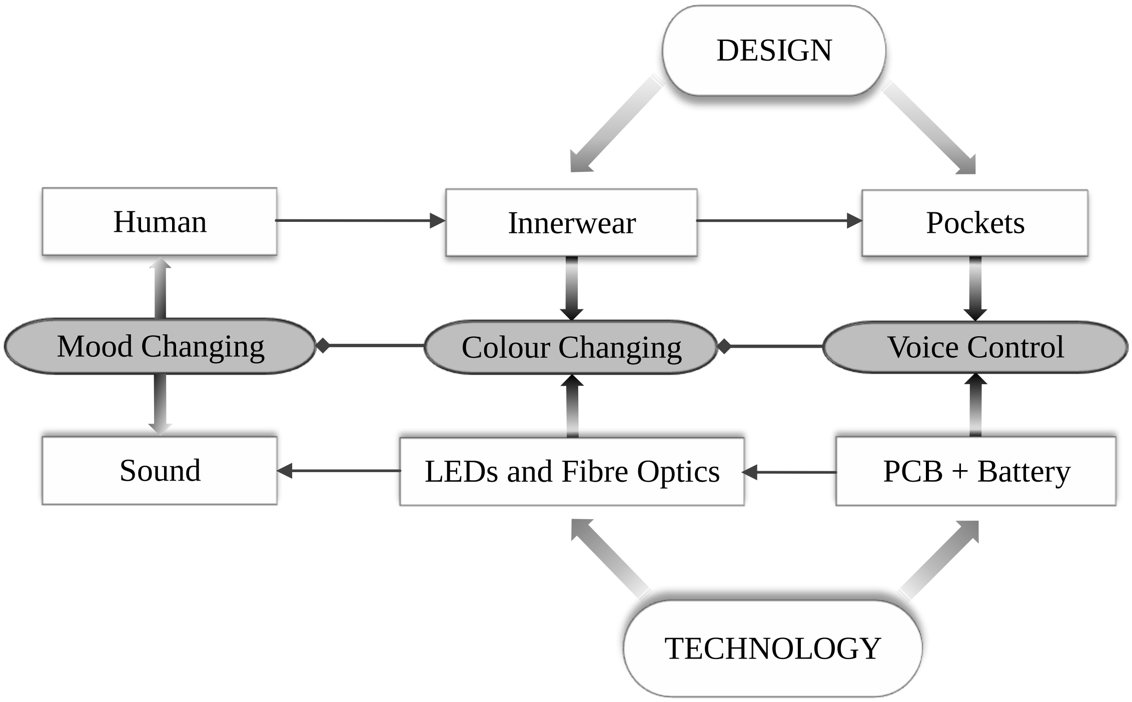


Figure 5.4 The information system

5.2.1 Mood changing technology

Based on smart wearable electronics, colour changing materials and mood changing technologies are integrated to explore the concept of smart ambience, where the user with the intimate environment can respond interactively. Sound, as one of the physiological changes related to psychological mood, can be detected by a microphone transducer. Programmable data processing is used to convert the signal to a corresponding colour change, triggered to represent a change of mood visually. RGB LEDs and fibre optics are designed as an array fabric matrix capable of displaying this colour change. A built-in microphone and a programmable microcontroller are integrated in a purposely designed and built PCB.

5.2.2 Innerwear design

Pockets have been designed and integrated in the smart clothing system to attach the PCB with careful consideration of the comfort of the human body. A lady's and a man's innerwear are carefully designed and prototyped in layers by luminescent fabrics connected to RGB LEDs and fibre optics, which can detect the mood of the wearer. To connect the transducer and the PCB with the output of the LEDs, the wiring circuitry is executed by fine wires and conductive fabrics.

5.2.3 Smart textile interface

Smart textile-based connections and clothing fasteners are created and packaged for serving the circuitry of the data system. As a smart interface, the luminescent fabrics of the innerwear garment can intelligently respond to both visual and functional changes, as the result of physiological/psychological changes.

Figures 5.5 and 5.6 illustrate the deployment of lady and man's innerwear design and mood changing technology through prototyping.

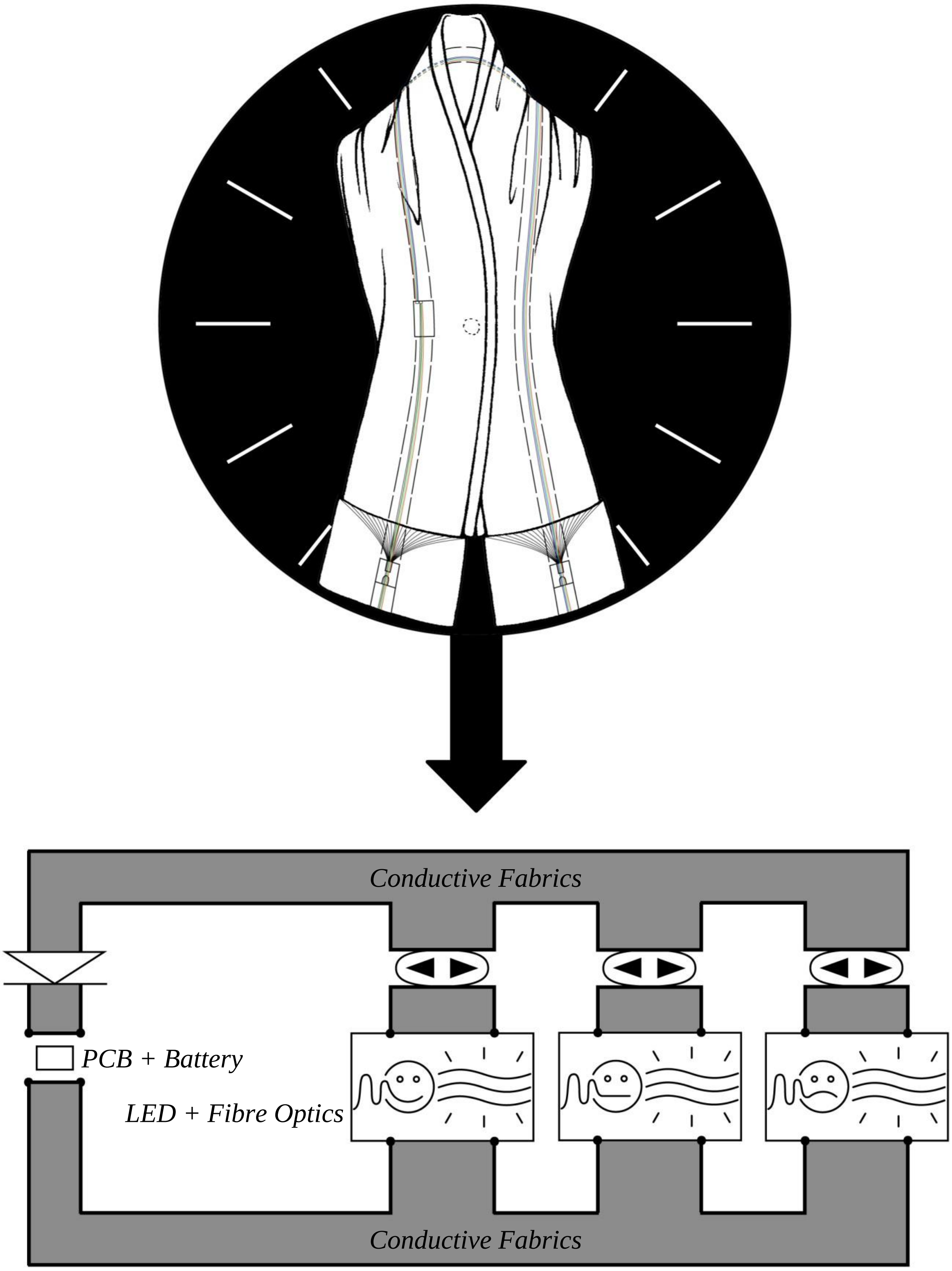


Figure 5.5 Mood changing technology and lady's innerwear design

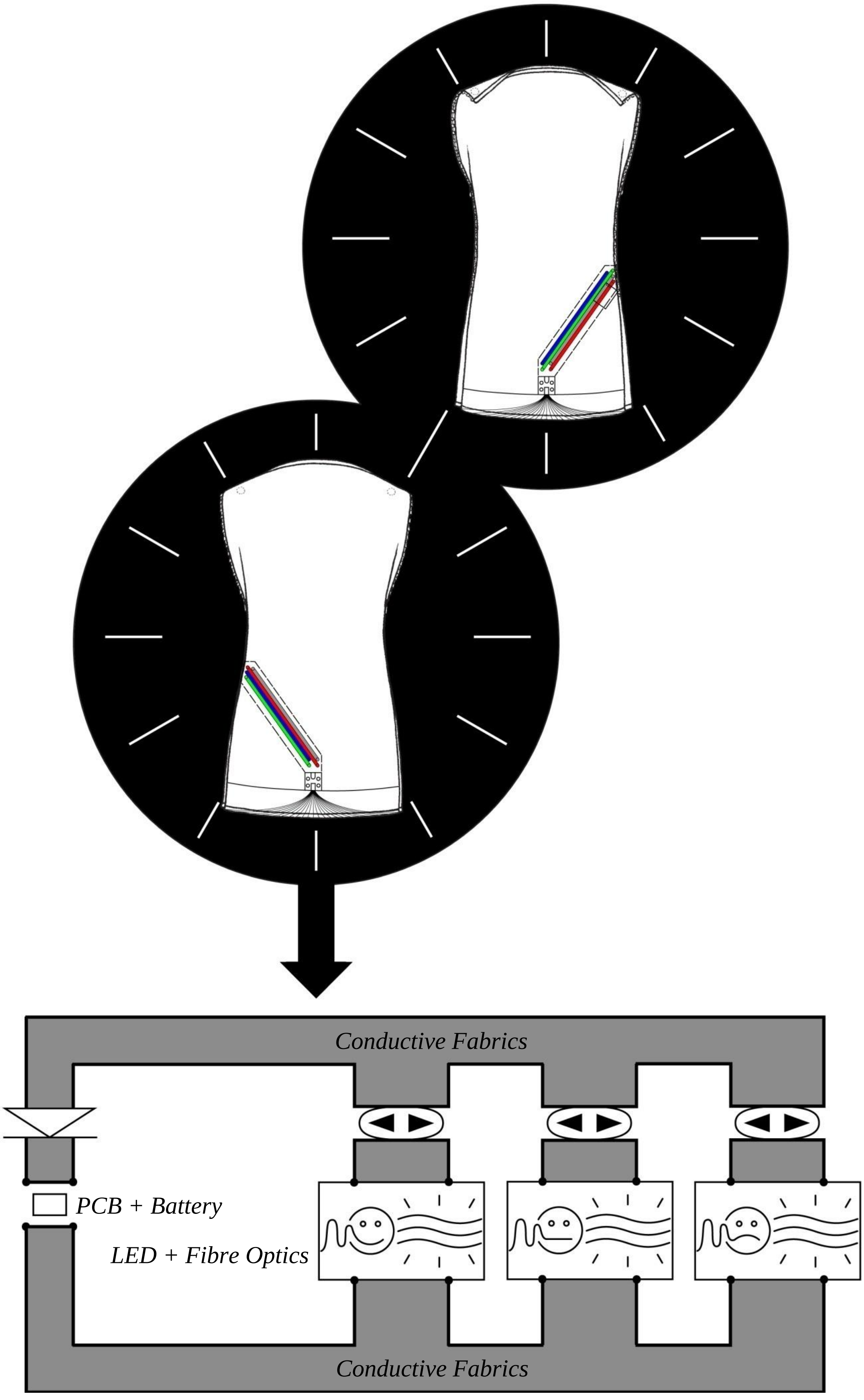


Figure 5.6 Mood changing technology and man's innerwear design

5.3 System Integration

The energy harvesting system and the information system are connected and integrated as shown in Figure 5.7.

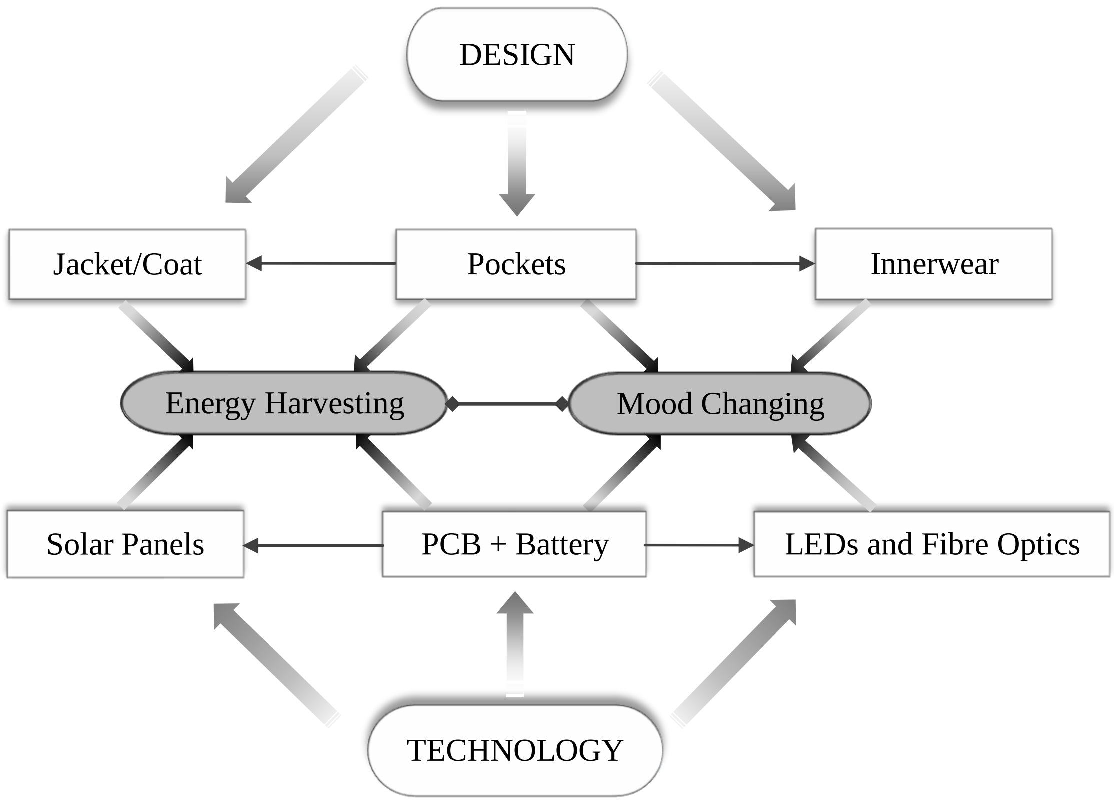


Figure 5.7 System integration

5.3.1 Energy and information systems

With the development of electronic environments, information technologies and interactive systems, smart ambience is based on the integration of the energy system and the information system in terms of storage, connectivity, display and feedback. Basically, an energy system with a continuous and sustainable power supply is important for energizing any information system. In Smart Environments and Intelligent Ambience, the information system fulfils the human needs and enriches the human's daily life. Therefore, the *user-centred design* in systems development is emphasized towards *what* we are designing and *who* is going to use it [88]?

5.3.2 Design and technology

In the application of smart textiles and wearable technologies for end-user demands, the "Critical Path" crosses the boundary between disciplines such as fashion design, textile technology and electronics need to be considered [89]. With new technology and by systematic design, smart clothing fashion has been developed as outfit collections in this project. The innerwear is the base layer to be worn closer to the body as “second skin”, and it carries the smart mood changing technology. Outside the base layer, a protective layer is designed to be the “outer shell”. This multi-functional outerwear is developed for weather-proofing and for supplying power. The outfit design needs to be carried out by applying of appropriate smart wearable technologies with tailor-made functionality and aesthetics.

Figures 5.9 and 5.10 illustrate the layering womenswear and menswear design underpinned with the integrated circuit diagrams as shown in Figure 5.8.

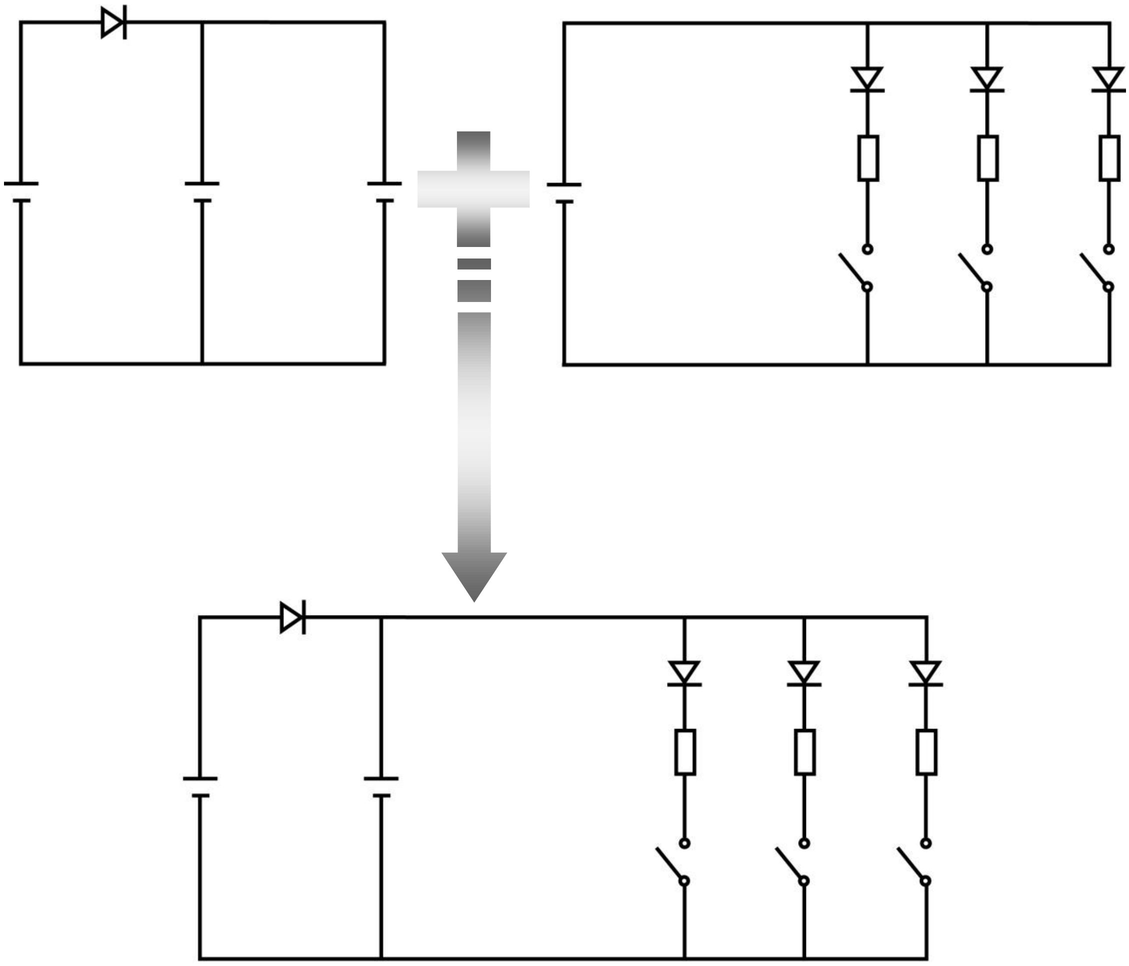


Figure 5.8 Integrated circuit diagrams

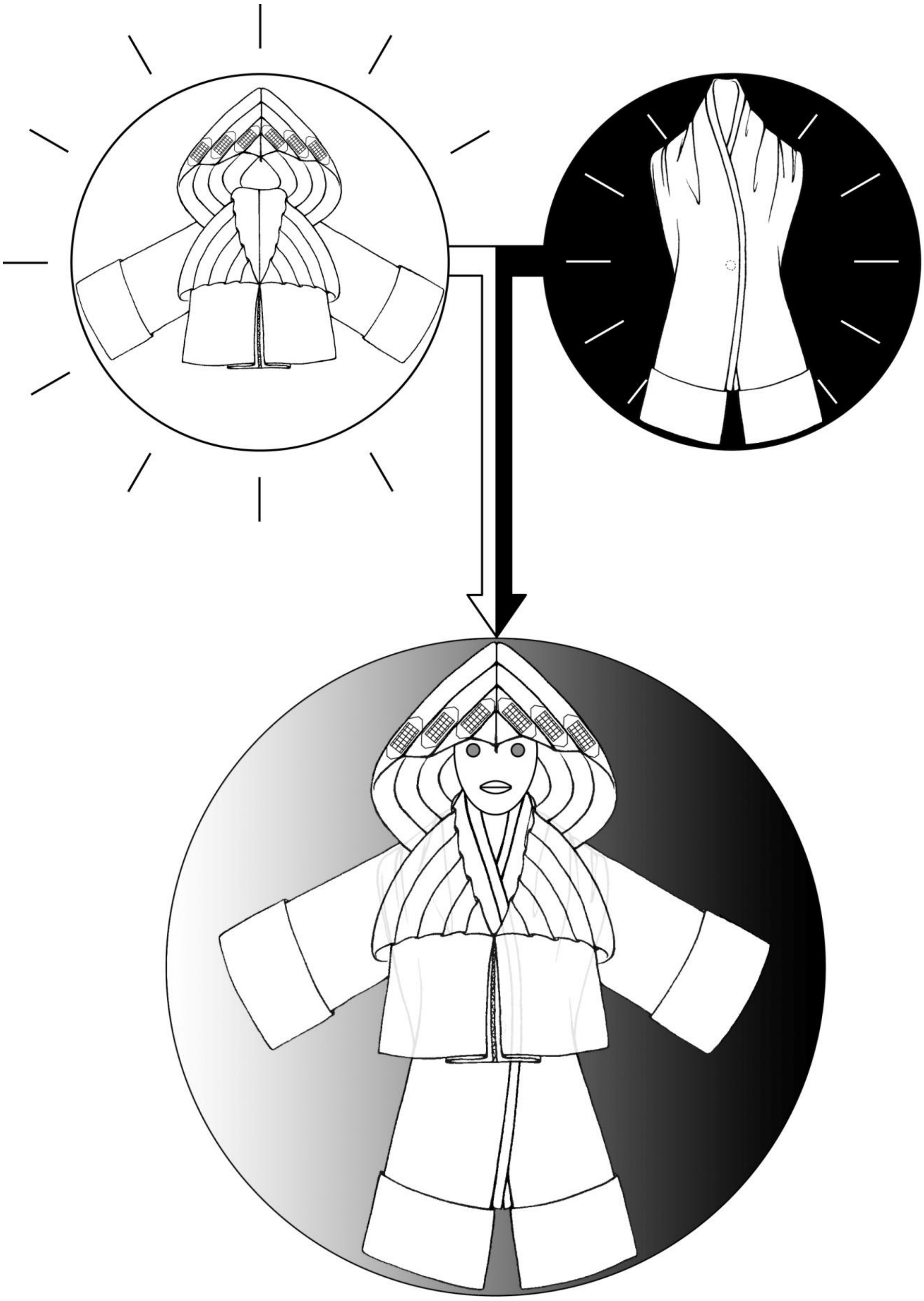


Figure 5.9 Layering womenswear

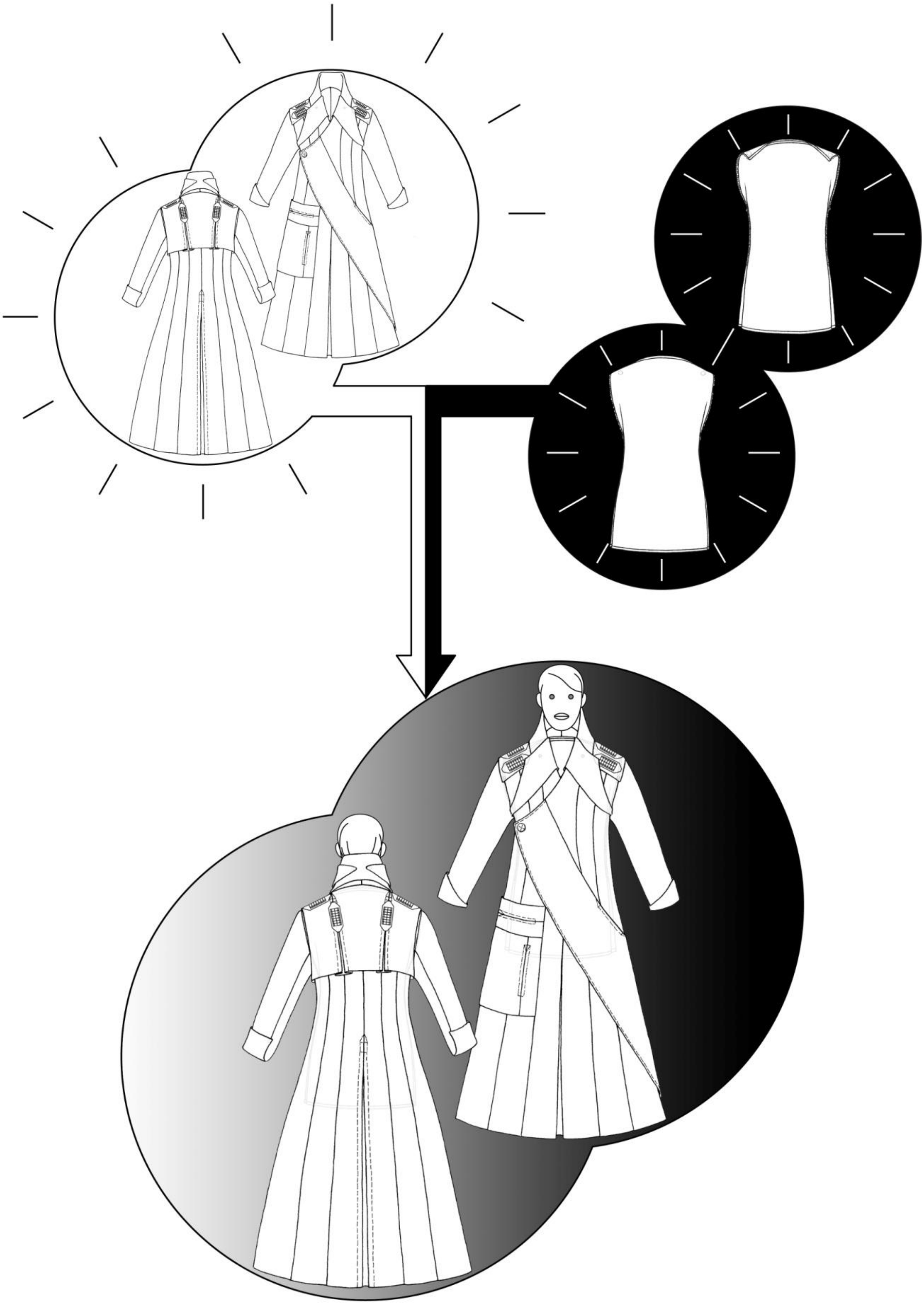


Figure 5.10 Layering menswear

CHAPTER 6 – WEARABLE ELECTRONIC DESIGN AND TECHNOLOGY DEVELOPMENT

To realize the innovative concept of this project, design/technology is implemented in a smart clothing system. Technology implementation shows to what extent technical development is possible, while design implementation presents the usability and aesthetic properties of the whole system. In a systems approach, aesthetics and functionality have been fused in harmony for the end-user. From design inspiration to technology innovation, this inventive project is realized through a creative process which includes component fabrication, electronics design and packaging, fabric and garment making up as well as consideration of clothing fitting. To achieve smart clothing, the technological devices should not only be small and flexible but also inconspicuous, so that they are only noticed by their actions, but not by their presence [90]. Although the terms fabrication, packaging, modularity and fitting seem to be technical words applied to mechanical, architectural, electronic and computing designs, their working principles and methods are also shared with fashion design and clothing manufacture.

6.1 Fabrication Design and Techniques

With consideration of every component, such as; solar panels, LEDs, fibre optics and circuitry components, fabrication and assembly of the non-fabric materials with fabrics are all essential parts for enabling functionality and aesthetics. When combining hard or semi-flexible electronics with stretchable and fully-flexible fabrics in clothing, dynamic stress concentration problems should be considered by skilful design and making up. Prefabrication methods have been used to assemble partial components of the whole system structure and testing their effectiveness before final clothing assembly. The interfaces for connecting and joining are constructed by different techniques. In particular, hot connection (soldering, welding, etc.), cold connection (snap, rivets, etc.) and adhesives have been used for joining of various parts. Aspects of jewellery fabrication have been considered and used for achieving beautiful, secure and functional connections [91].

6.1.1 Circuitry

Before designing the prefabrication/fabrication of each component, the circuitry between two components has to be tried and its suitability established. This includes the conductive pathway of the circuitry with the corresponding connectors. For example, the conventional circuitry in the clothes usually consists of fine and flexible wires and male plug or female socket connectors as shown in Figure 6.1, connected with the other components by soldering techniques.

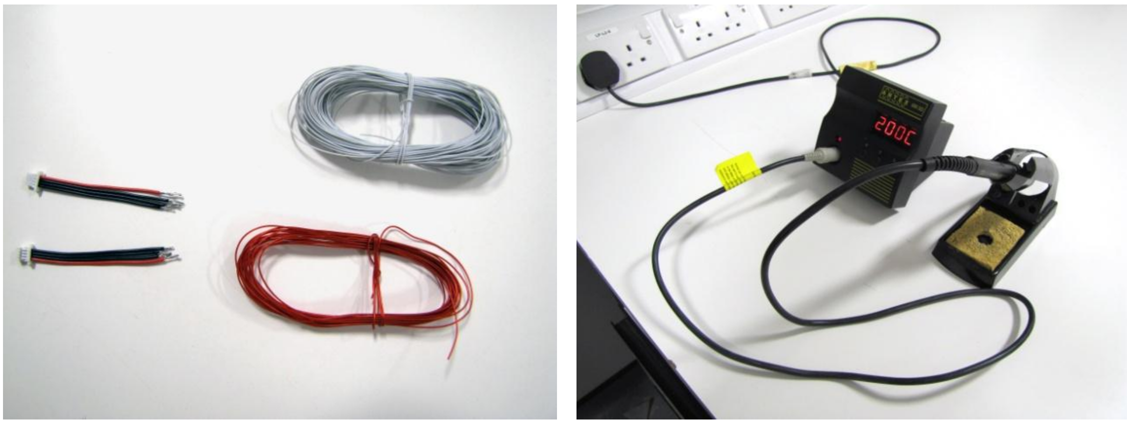


Figure 6.1 Fine and flexible wires, plug connectors and soldering machine

Although the wires used are fine and flexible, they are nevertheless non-fabric materials with limited flexibility compared with textile-based conductive fabrics as shown in Figure 6.2.

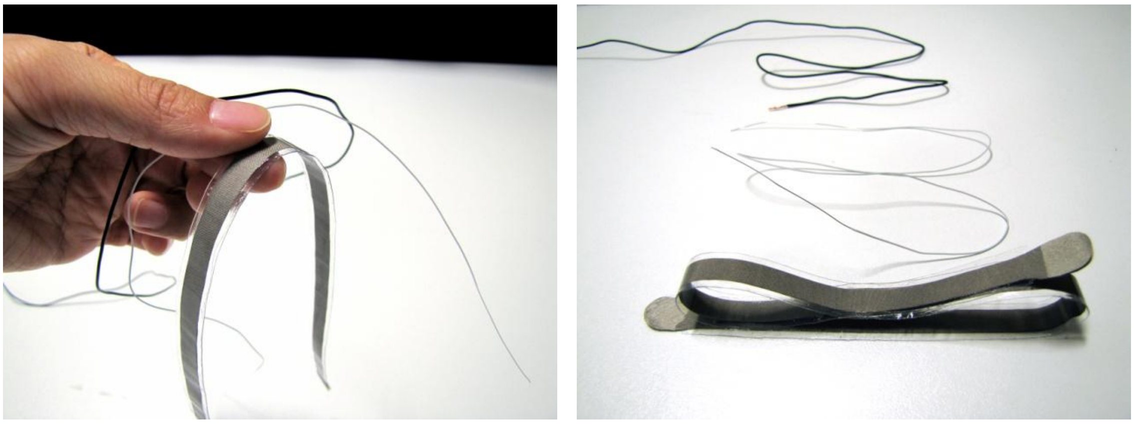


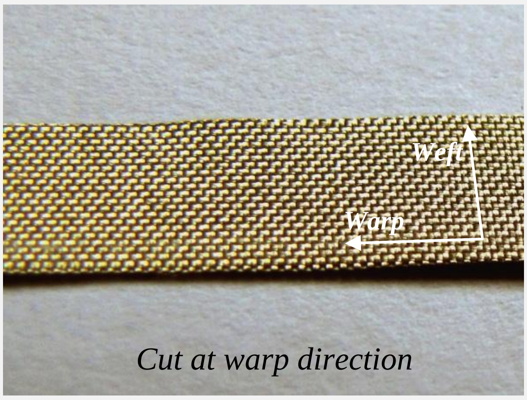
Figure 6.2 Comparable flexibility of the wires and conductive fabrics

In this project, a novel flexible connection has been devised of textile-based circuitry to replace traditional wires. Electronylon Nickel is one of the conductive fabrics used as a textile-based circuitry path or wire. As seen in Figure 6.3, this high-strength rip-stop fabric is composed of high quality polyester taffeta fabric as a woven substrate, coated with a copper and nickel plating, providing exceptional electrical conductivity [92]. Copper and nickel alloy snap fasteners of the size no. 15 have been used on clothing as on and off connectors. A snap punch machine is used to attach them on the fabric, as shown in Figure 6.3.

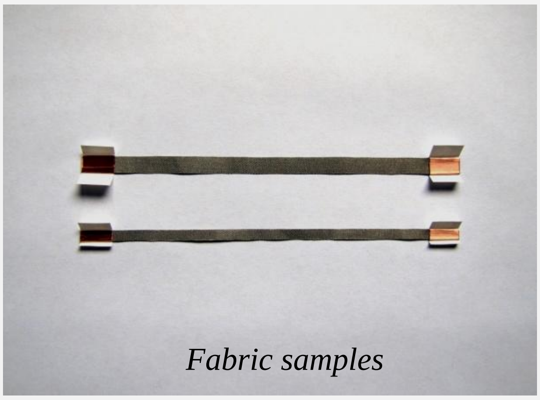
Figure 6.3 Textile-based conductive fabrics, fastening connectors and punch machine

Since fabric construction and plating consistency will affect conductivity, the chosen conductive fabrics have been investigated by testing of different structural shapes and dimensions. Tables 6.1 – 6.5 displays the electrical characteristics per 100mm measured on 3mm and 5mm wide strips in weft, warp, 45°, 30° and 15° of fabric direction. After a number of experiments, Electronylon Nickel in the warp direction shows the best results in low and stable resistance value range.

Cut Fabric Samples



Cut at warp direction

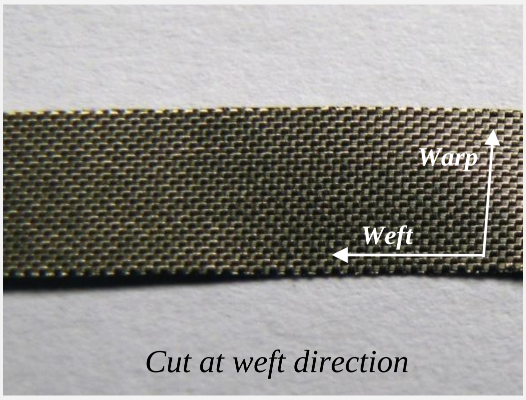


Fabric samples

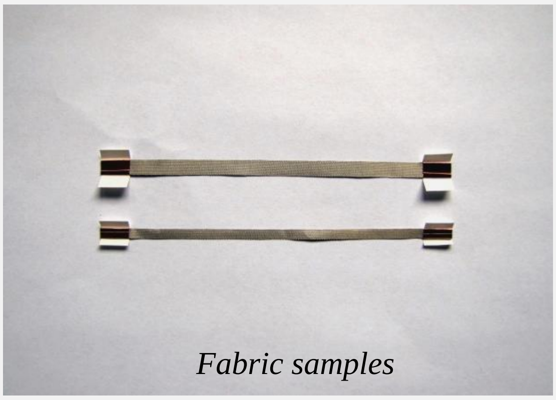
Direction of Fabric Cut	Warp			
Length (mm)	100			
Width (mm)	3		5	
Operating Current (mA)	**Operating Voltage (mV)**	**Resistance (Ohm)**	**Operating Voltage (mV)**	**Resistance (Ohm)**
100	28.79	3.47	17.51	5.71
200	58.26	3.43	35.28	5.67
300	86.90	3.45	52.86	5.68
400	115.75	3.46	70.92	5.64
500	148.50	3.37	88.94	5.62
600	176.49	3.40	107.45	5.58
800	239.60	3.34	143.58	5.57
1000	304.50	3.28	182.70	5.47

Table 6.1 Electrical characteristics of Electronylon Nickel at warp direction fabric cut

Cut Fabric Samples



Cut at weft direction

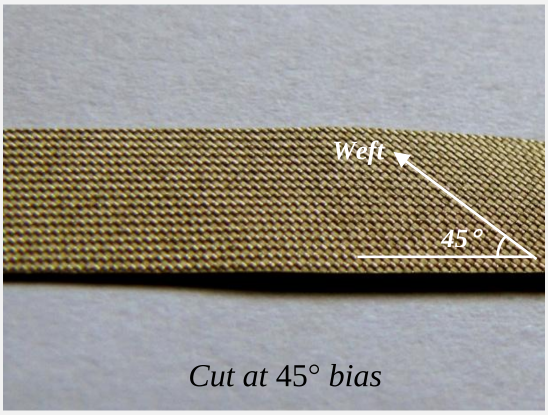


Fabric samples

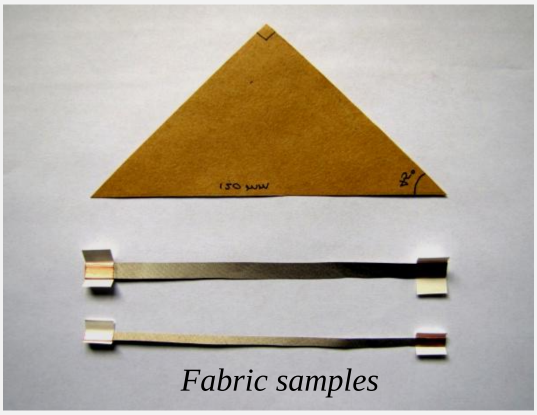
Direction of Fabric Cut	Weft			
Length (mm)	100			
Width (mm)	3		5	
Operating Current (mA)	**Operating Voltage (mV)**	**Resistance (Ohm)**	**Operating Voltage (mV)**	**Resistance (Ohm)**
100	24.86	4.02	15.53	6.44
200	49.66	4.03	31.06	6.44
300	75.64	3.97	46.65	6.43
400	100.43	3.98	62.88	6.36
500	127.13	3.93	77.90	6.42
600	151.48	3.96	93.80	6.40
800	206.50	3.87	127.98	6.25
1000	257.56	3.88	160.10	6.25

Table 6.2 Electrical characteristics of Electronylon Nickel at weft direction fabric cut

Cut Fabric Samples



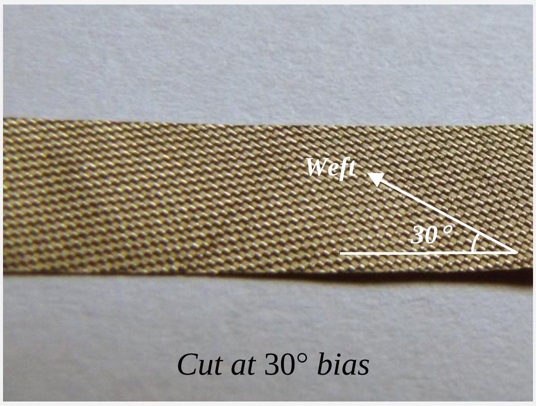
Cut at 45° bias


Fabric samples

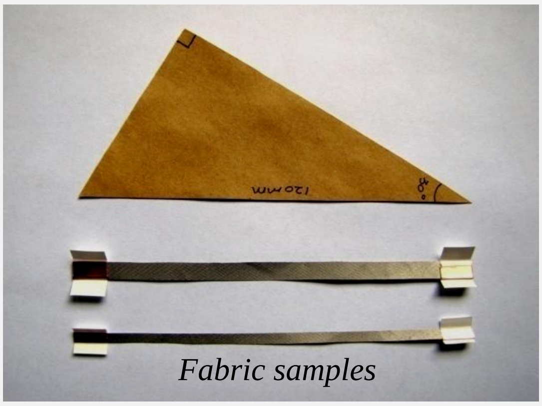
Direction of Fabric Cut	45°			
Length (mm)	100			
Width (mm)	3		5	
Operating Current (mA)	**Operating Voltage (mV)**	**Resistance (Ohm)**	**Operating Voltage (mV)**	**Resistance (Ohm)**
100	29.51	3.39	17.07	5.86
200	59.18	3.38	34.06	5.87
300	89.30	3.36	51.25	5.85
400	119.79	3.34	68.56	5.83
500	150.50	3.32	86.02	5.81
600	182.31	3.29	103.46	5.80
800	249.24	3.21	139.12	5.75
1000	317.70	3.15	175.97	5.68

Table 6.3 Electrical characteristics of Electronylon Nickel at 45 ° direction fabric cut

Cut Fabric Samples



Cut at 30° bias


Fabric samples

Direction of Fabric Cut	30°			
Length (mm)	100			
Width (mm)	3		5	
Operating Current (mA)	**Operating Voltage (mV)**	**Resistance (Ohm)**	**Operating Voltage (mV)**	**Resistance (Ohm)**
100	36.10	2.77	16.09	6.22
200	71.79	2.79	31.94	6.26
300	107.95	2.80	48.24	6.22
400	144.45	2.77	64.31	6.22
500	179.50	2.79	80.50	6.21
600	218.29	2.75	96.61	6.21
800	295.93	2.70	130.18	6.15
1000	371.65	2.69	163.95	6.10

Table 6.4 Electrical characteristics of Electronylon Nickel at 30° direction fabric cut

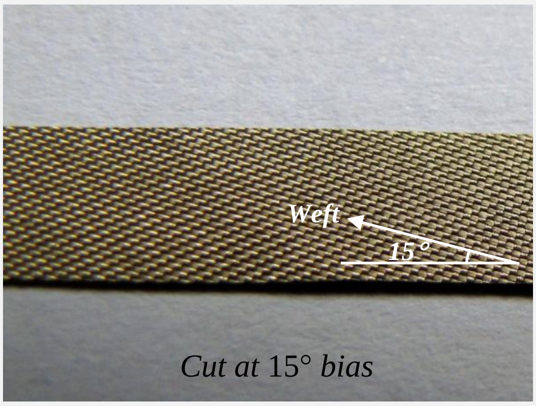
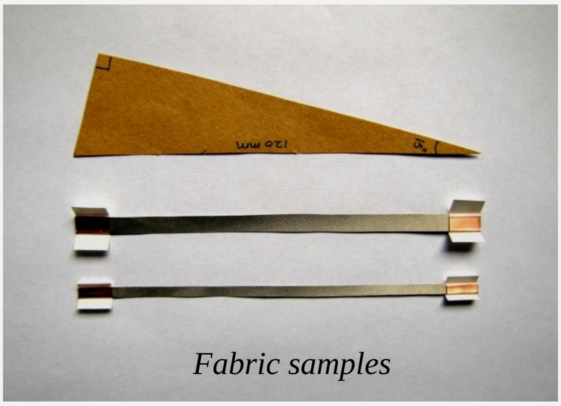
Cut Fabric Samples				
 Cut at 15° bias	 Fabric samples			
Direction of Fabric Cut	15°			
Length (mm)	100			
Width (mm)	3		5	
Operating Current (mA)	**Operating Voltage (mV)**	**Resistance (Ohm)**	**Operating Voltage (mV)**	**Resistance (Ohm)**
100	25.02	4.00	15.73	6.36
200	50.08	3.99	31.42	6.37
300	75.20	3.99	47.06	6.37
400	100.76	3.97	62.70	6.38
500	125.53	3.98	79.08	6.32
600	152.60	3.93	95.43	6.29
800	206.55	3.87	127.60	6.27
1000	260.90	3.83	160.21	6.24

Table 6.5 Electrical characteristics of Electronylon Nickel at 15° direction fabric cut

6.1.2 Solar panels with connectors

Since a small and flexible solar panel unit is chosen as stated in Chapter 3, specific mounting design and connecting techniques are required to connect single solar panel in a photovoltaic array for the required output current.

An adhesive is applied to attach the solar films onto a fabric. The silver/copper terminals of the solar films are extended by adhering conductive fabrics with Silver Epoxy Adhesive, as shown in Figures 6.4 and 6.5.

Figure 6.4 Silver Epoxy Adhesive

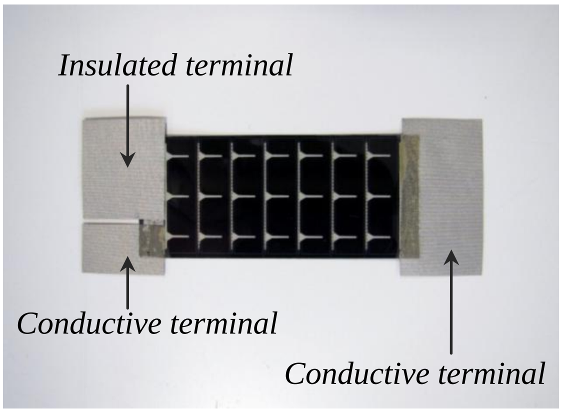


Figure 6.5 Terminal extensions

Schottky Barrier Diodes are used to protect the electric current for each solar panel. They are connected between the positive and negative terminals of each panel (Figures 6.6 and 6.7) by soldering as shown in Figure 6.8.

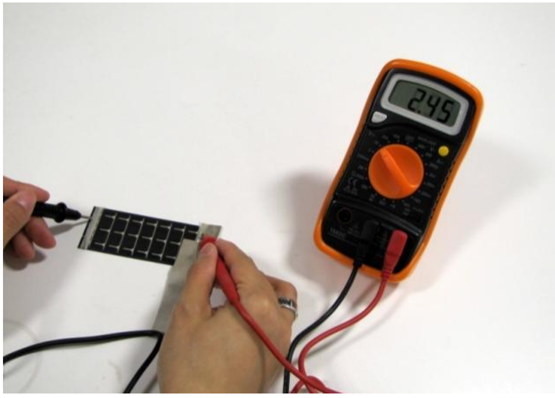


Figure 6.6 Design and test the connecting part between the positive and negative terminals

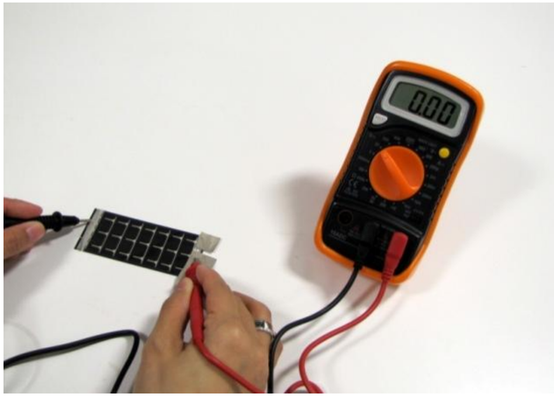


Figure 6.7 Design and test the disconnecting part between the positive and negative terminals

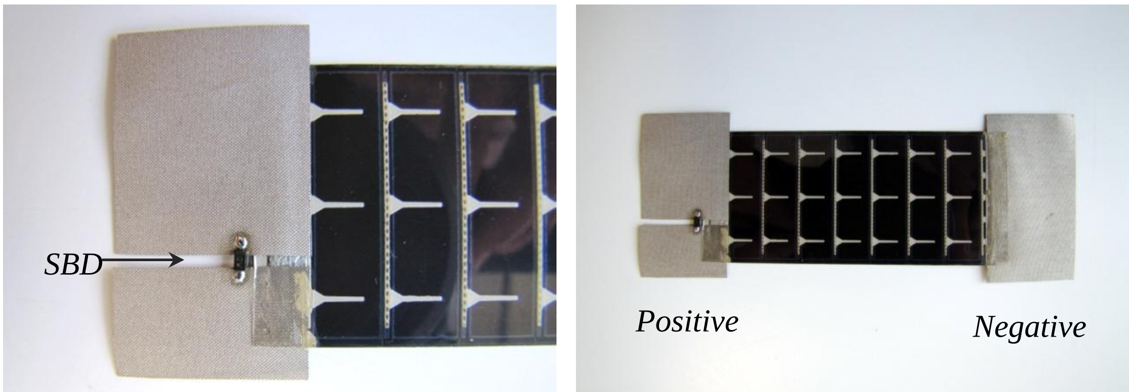


Figure 6.8 SBD insertion and soldering

The entire reverse side of the solar film and the conductive terminals are heat-sealed with water-proof Gore-Tex fabrics using double-sided PU thermoplastic adhesive tapes, as shown in Figures 6.9 – 6.11.

Figure 6.9 PU thermoplastic adhesive

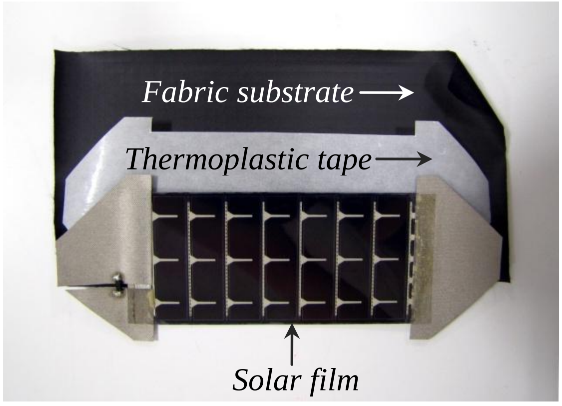


Figure 6.10 Sandwich structure

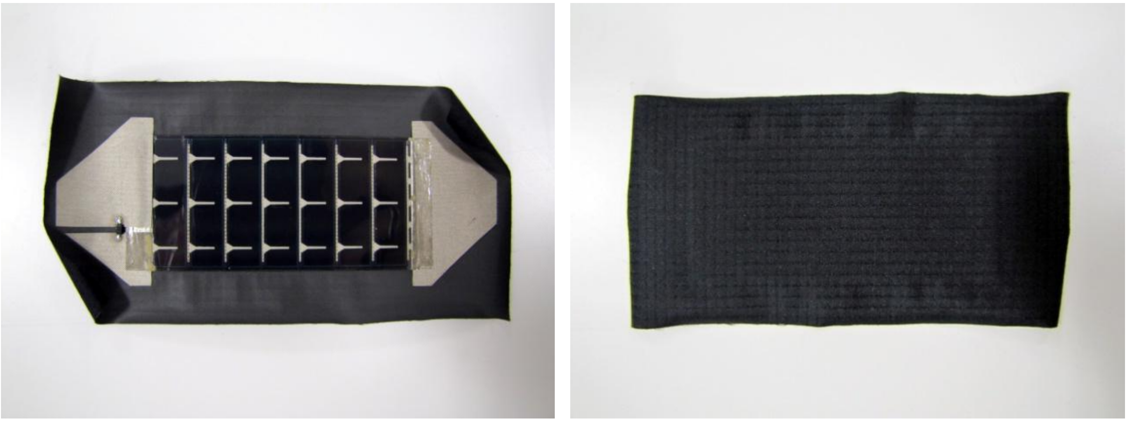


Figure 6.11 Solar panel adhered with the fabric substrate – Front and rear

The electrodes of the solar films are designed to be removable by using snap fasteners as shown in Figure 6.12.

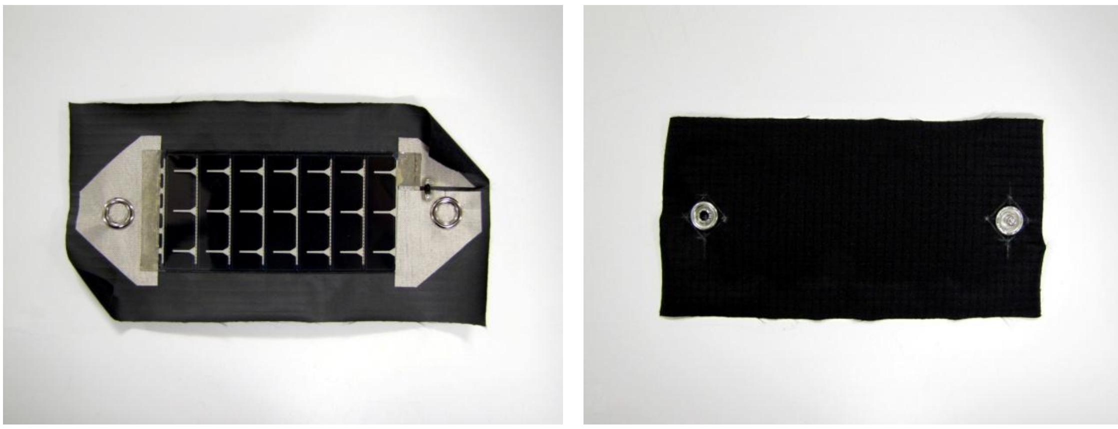


Figure 6.12 Connection of solar panel electrodes by snap fasteners – Front and rear

6.1.3 LEDs with connectors

For the luminescent part, the connection of the LEDs through extended leads with the other parts of the system is another challenge. To improve the efficiency of the system, mini flexible wire soldering and connections with novel conductive fabric have been investigated.

Figures 6.13 – 6.14 show flexible fine wires soldered with LED leads on one side and the mini connector pins on the other, by using a 0.5mm pointed soldering iron tip and 0.5mm solder wire.

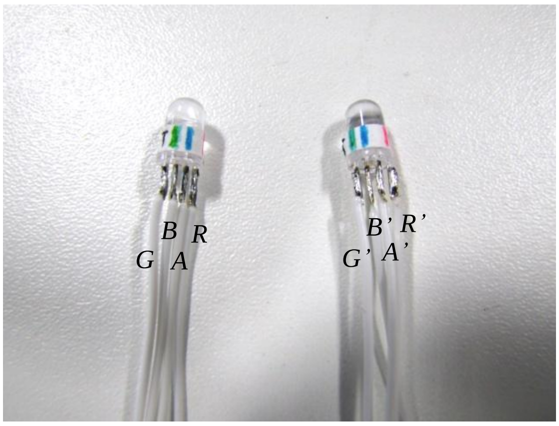


Figure 6.13 LEDs soldering – A=Common Anode, R=Red, G=Green, B=Blue

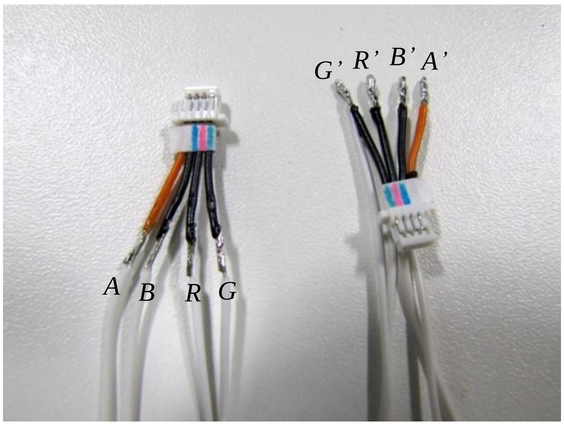


Figure 6.14 Mini connectors soldering – A=Common Anode, R=Red, G=Green, B=Blue

On the other hand, conductive fabrics have been successfully tried to replace the long wires as seen in Figures 6.16, according to the careful design illustrated in Figure 6.15. In order to avoid stress concentration problems which usually happen in the connections between rigid materials and flexible fabrics, the LED leads and mini connectors are not soldered directly on the conductive fabrics, but connected by snap fasteners. As shown in Figures 6.17 and 6.18, sections of wire extensions to LED leads and mini connectors are used to damp the stress concentration.

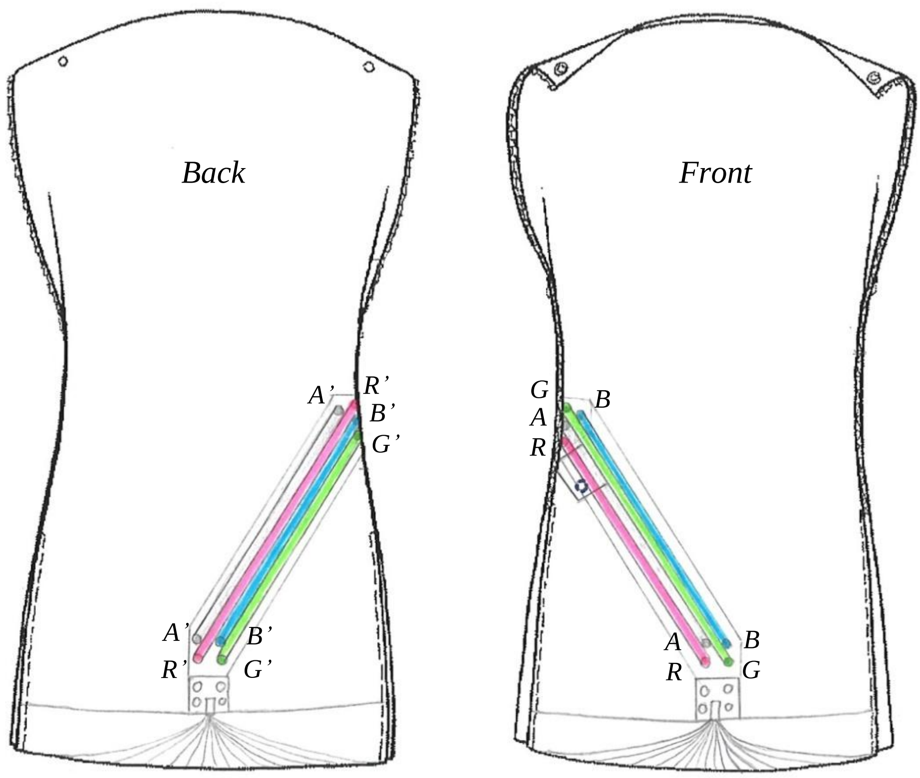


Figure 6.15 Man's innerwear design to use conductive fabric circuitry between the LEDs and connectors – Front and back, A=Common Anode, R=Red, G=Green, B=Blue

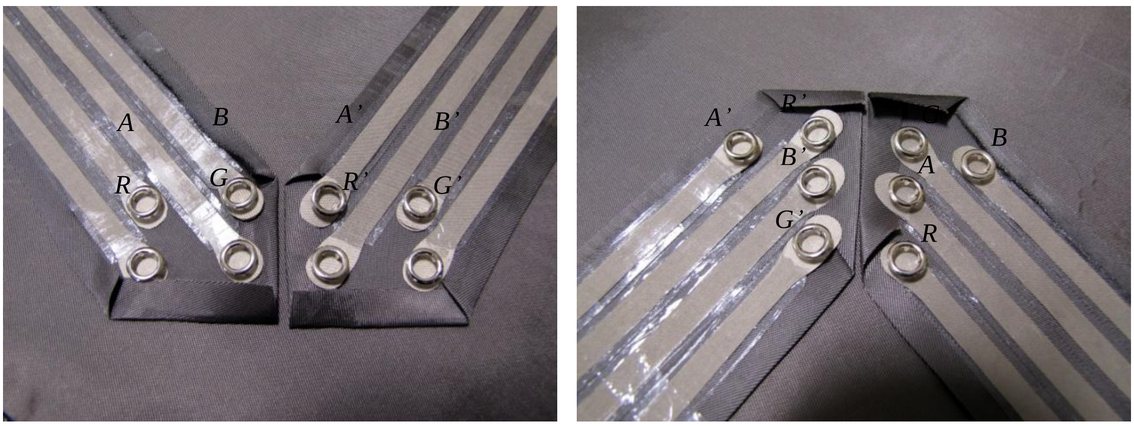


Figure 6.16 Snap fastening terminals for the fabricated circuitry – A=Common Anode, R=Red, G=Green, B=Blue

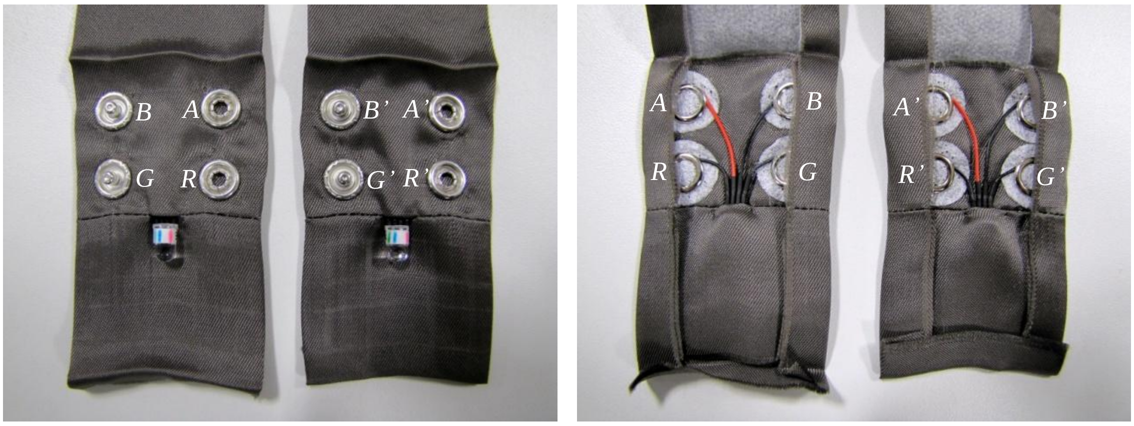


Figure 6.17 Wire extension and fastening of the LEDs – Outside and inside, A=Common Anode, R=Red, G=Green, B=Blue

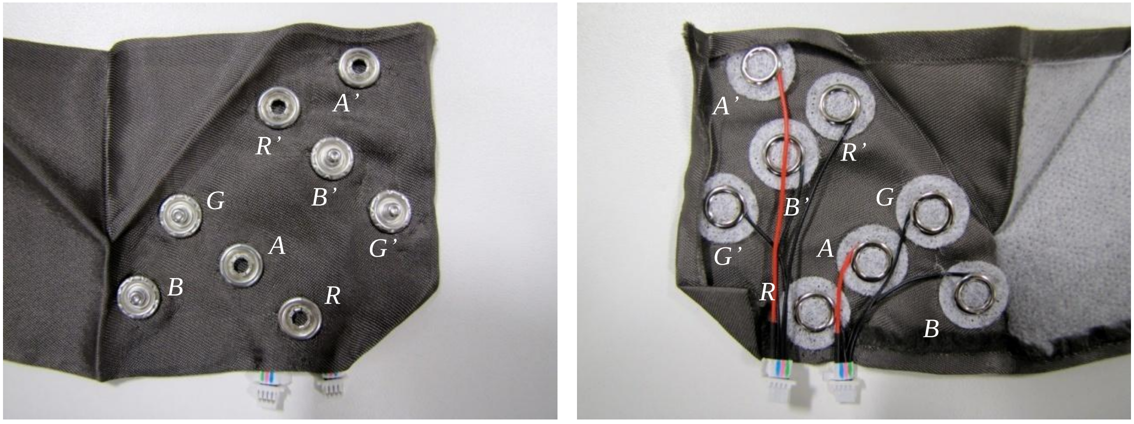


Figure 6.18 Wire extension and fastening of the mini connectors – Outside and inside, A=Common Anode, R=Red, G=Green, B=Blue

After the fabrication of each part, testing of the connections has been carried out and proved the working of this part of the system.

6.1.4 Fibre optic harness

To transfer and magnify the illumination from LEDs to the luminescent fabrics, bundles of the optical fibre ends need to be connected with LEDs as shown in Figure 6.19.

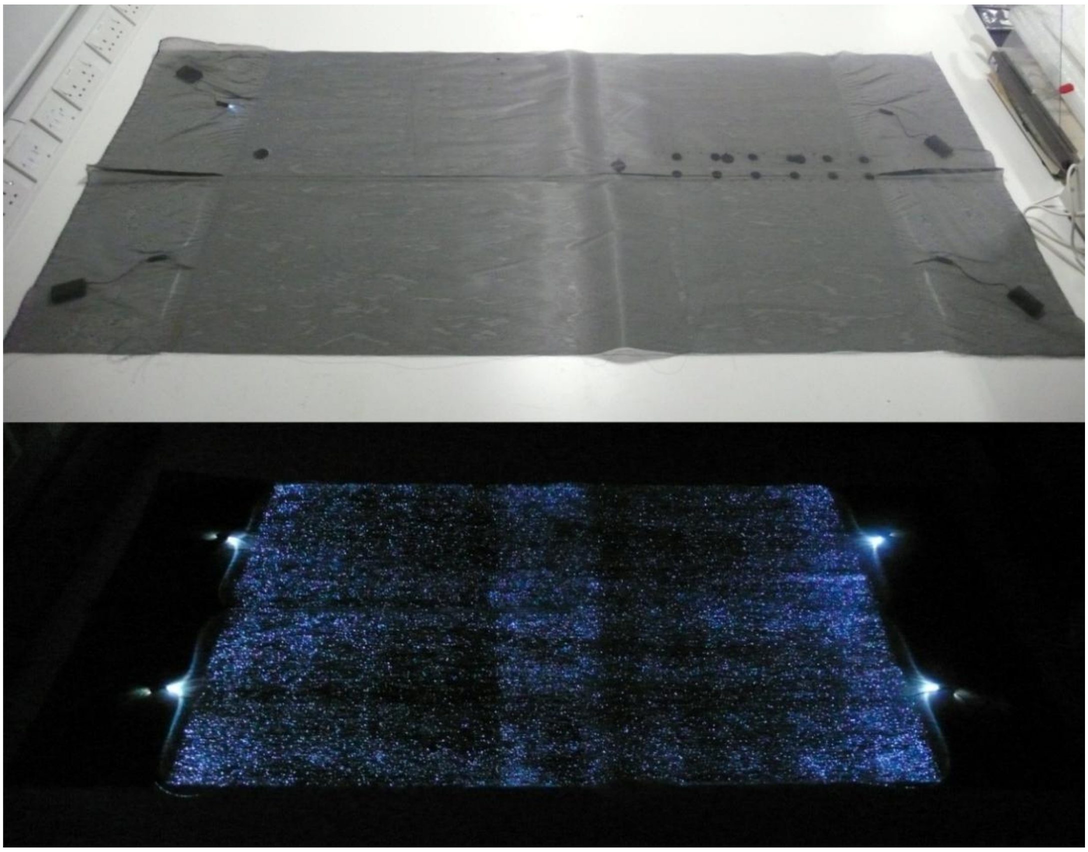


Figure 6.19 Luminescent fabrics lighted by LEDs through optical fibre bundling

Typically, the optical fibre bundle and LED are connected to each other by a bushing socket shown in Figure 6.20. This connecting mechanism can be pushed in and held securely. But any rigid bushing and bulky battery pack are not comfortable for wearing.

Figure 6.20 Conventional bushing harness to connect the optical fibre bundles and LEDs

In this project, a creative harness design has been designed and made up of snap fasteners and flexible fabric layers which could be snapped on and taken off easily, as shown in Figure 6.21, also providing washability and good maintenance properties. A pair of cylindrical moulds acts as linings inside the main fabric layers with precise positioning to hold the fibre bundle and LED securely and are also hidden away.

Figure 6.21 Creative fastening harnesses to connect the optical fibre bundles and LEDs

6.2 Packaging, Modular Design and Techniques

During fabricating and integrating of the electronic parts, care has been taken to consider the need of wearers and the requirements of their daily use. In the design of electronic appliances and interactive systems, the shortcomings of existing models are responsive through the "user experience" by reconsidering what we are designing [88]. A profound design space is considered by providing the smart clothing with wearable electronics, such as the design and techniques of packaging and modularity highlighted in this project have been undertaken for fulfilling the following objectives:

- Protect against exposure to extreme weather and dirt, body contact and mechanical damage;
- Aesthetic appearance and convenient user interface;
- Ease of access to internal parts for good maintenance;
- Effectively reduce wastage of resources, multiply the usage of intelligent technology and enhance the lifespan of smart fashion.

Packaging refers to objects requiring design for protection, distribution, storage and usage [93]. With regard to the electronic components used in circuitry, solar films, LEDs, PCB and battery, the integrative and protective features are necessary to be built into both the components and the final clothes. For best integration with clothing, packaging objectives and practical considerations need to be balanced by trying various technologies.

6.2.1 Circuitry packages

Although circuitry is designed to be embedded into the fabric layers in the clothes, the circuit pathway and connecting points still need to be protected. In the case of wiring circuitries, 4mm diameter black heat shrink tubes have been used and are shrunk by a hot air machine to insulate and reinforce the exposed soldering points, as shown in Figures 6.22 and 6.23.

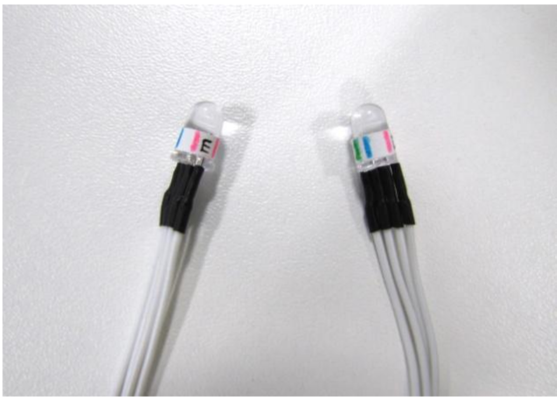


Figure 6.22 Insulation of the soldering LEDs

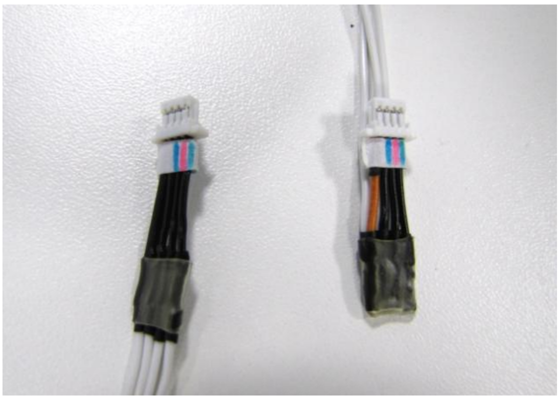


Figure 6.23 Insulation of the soldering mini connectors

For the newly designed circuitry, the entire conductive fabrics are coated by noncorrosive and adhesive sealant for insulation purposes, as shown in Figure 6.24. This insulation method is also applied to the connecting points which are made up by metal snaps, as shown in Figure 6.25.

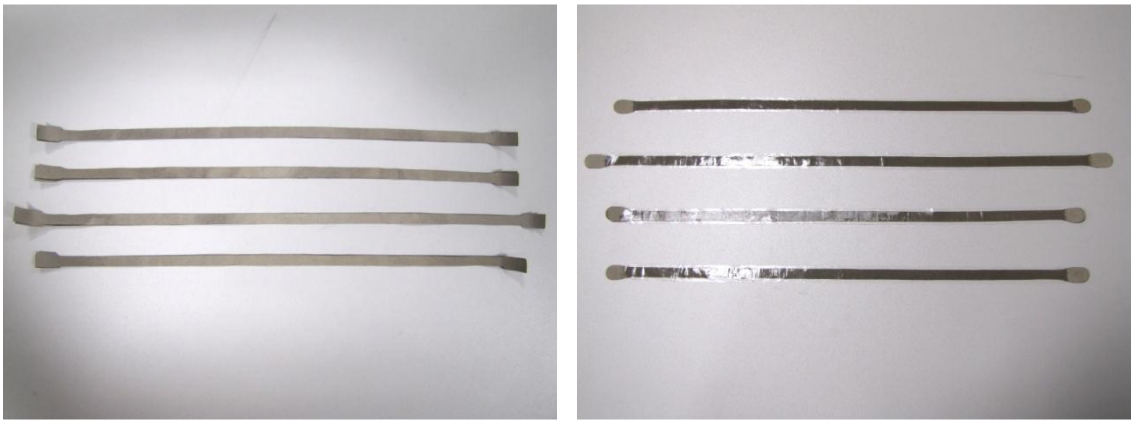


Figure 6.24 Insulation of the conductive fabric circuitry – Before and after

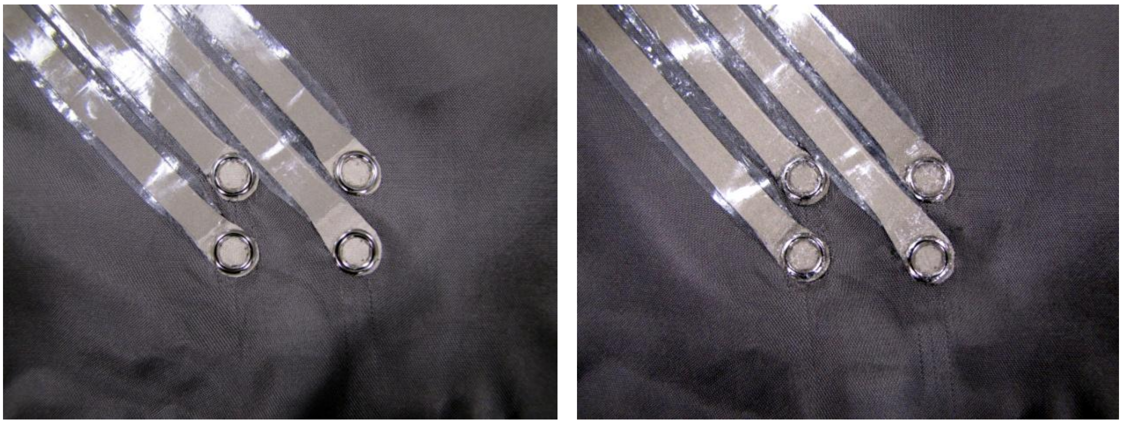


Figure 6.25 Insulation of the connecting points – Before and after

6.2.2 Solar films packaging

Requiring good exposure to the sunlight but also being well secured on the clothing, specific packages have been designed for the solar films in primary and secondary packaging. Each prefabricated solar film is made as an envelope and held together by waterproof fabrics, through folding, applying adhesive and stitching. A series of photos in Figure 6.26 show the making up process of the primary packaging for the solar films.

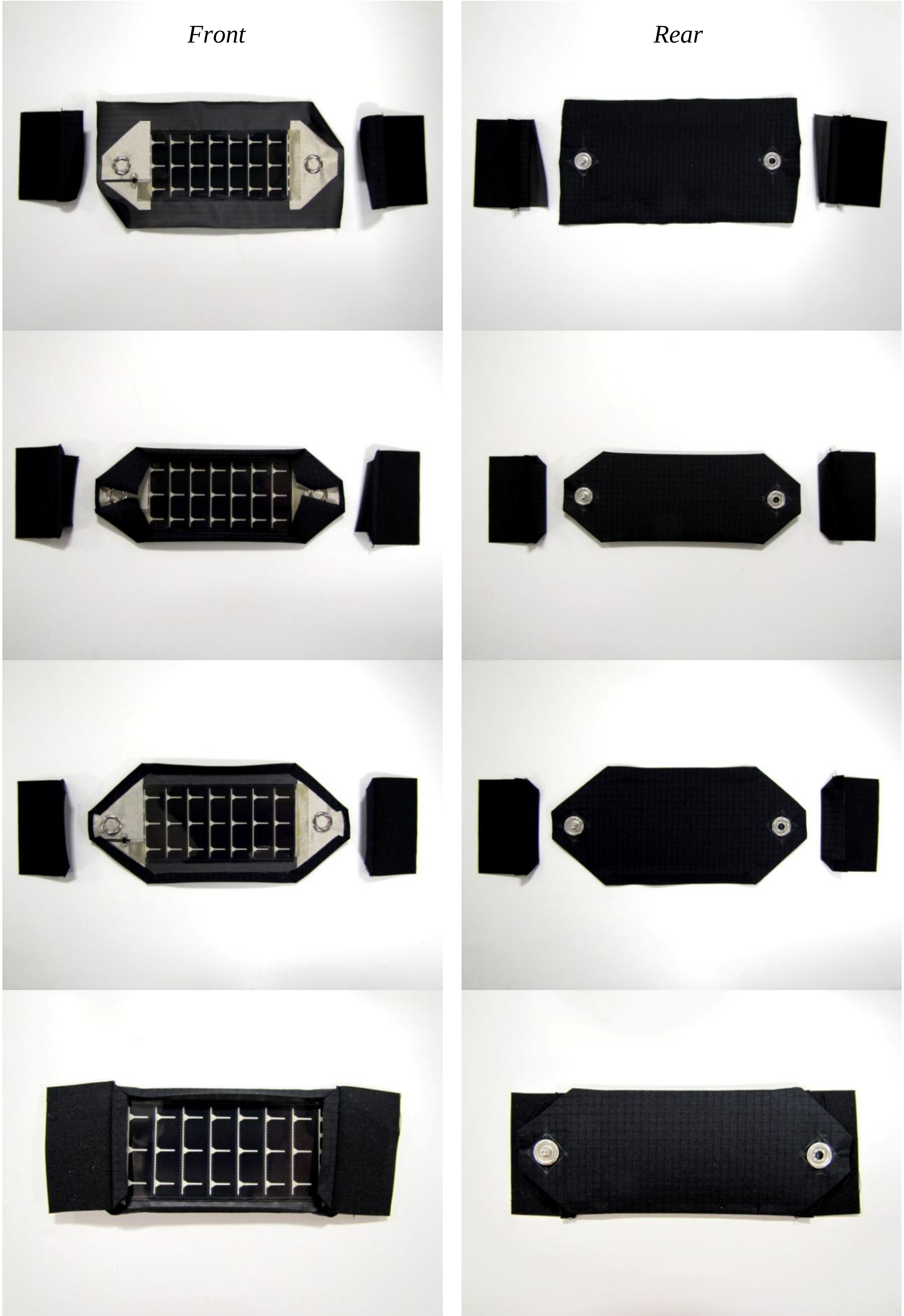

Front
Rear

Figure 6.26 A series of photos to display the making process of the solar films packaging — Front and rear

After primary packaging, individual solar films are being grouped together by secondary packaging. Figures 6.27 – 6.30 shows the “pouch”-like design to package and protect each panel easily, also acting as a clothing accessory which blends into clothing whilst also being a functional charging tool.

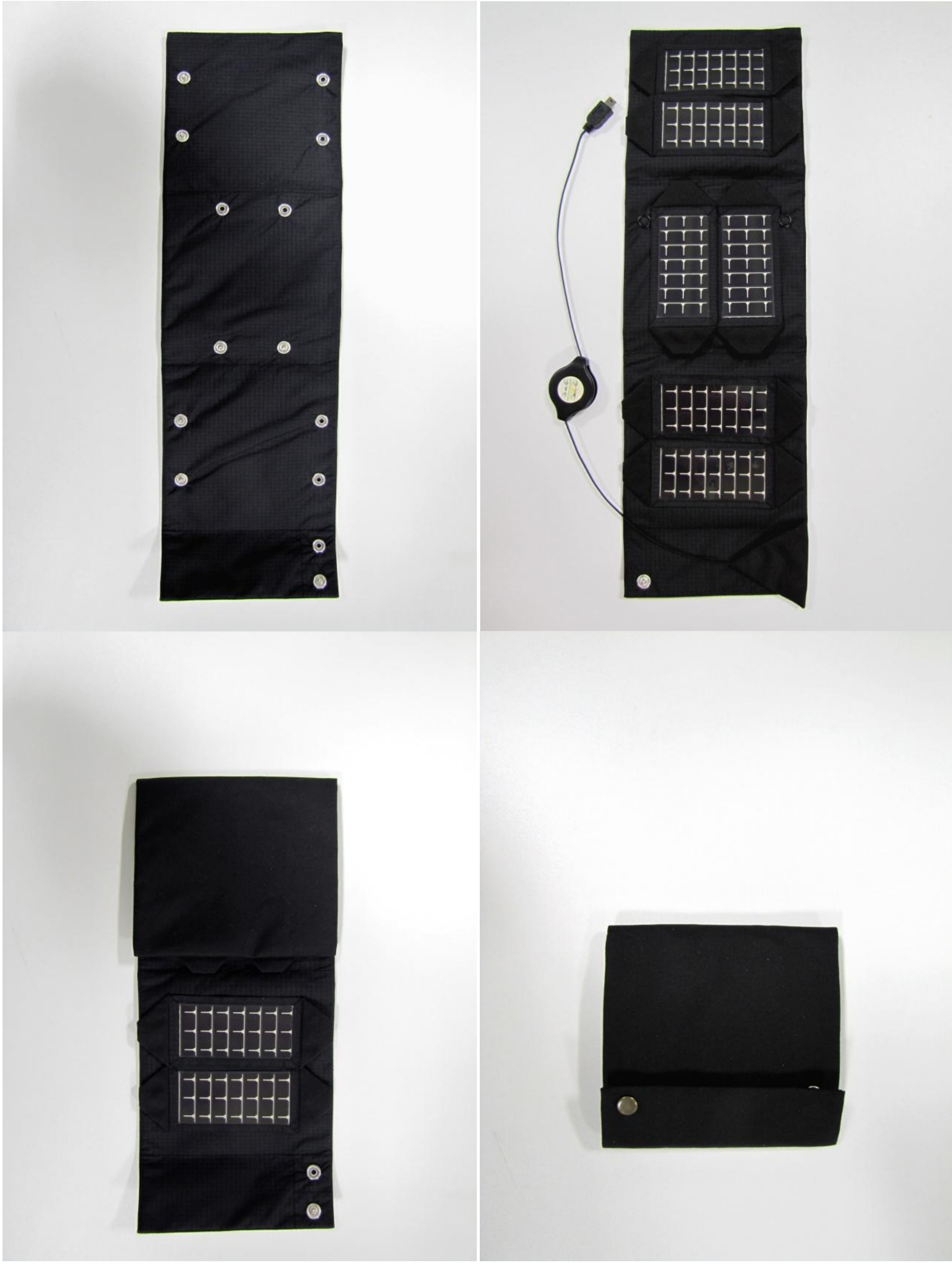


Figure 6.27 "Pouch"-like design to package and protect solar films for menswear

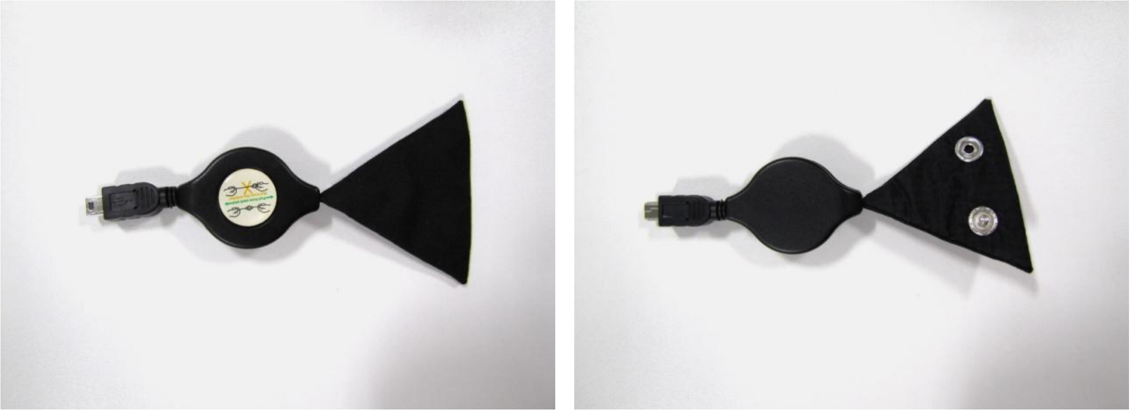


Figure 6.28 Packaging of charging connector for menswear — Front and rear

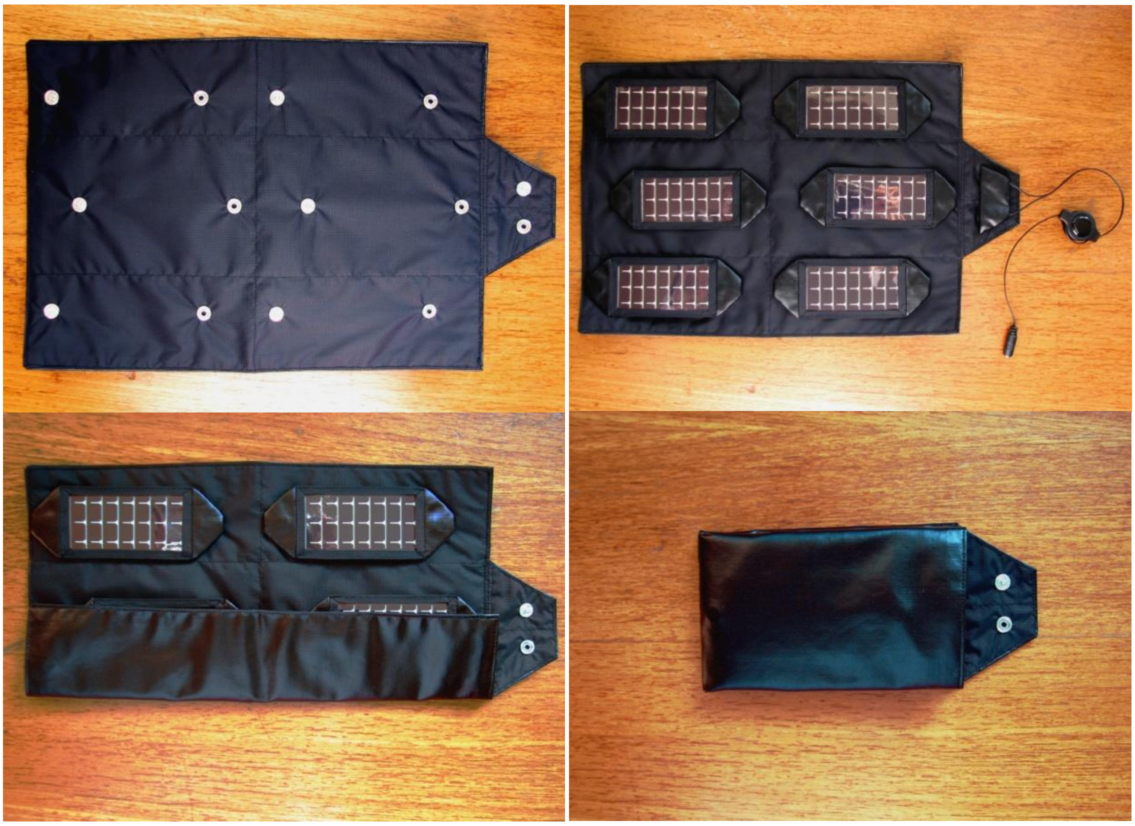


Figure 6.29 "Pouch"-like design to package and protect solar films for womenswear

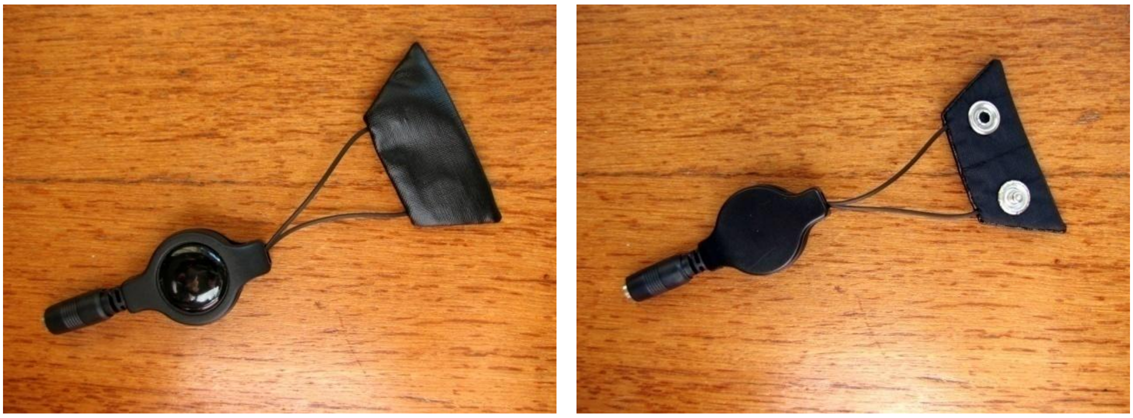


Figure 6.30 Packaging of charging connector for womenswear — Front and rear

6.2.3 Packages for LEDs, connectors and optical fibre harness

As previous stated, LEDs and optical fibres are packaged in a harness design and work together to provide lighting of the luminescent fabrics. In the fabric-based packaging, the protruding optical fibres are concealed in the layered fabric by careful handling. Different style designs have been considered for the lady's and man's innerwear garments, with LED lighting sources packaged in different ways.

Figure 6.31 displays the shaped luminescent fabric in the lady's innerwear design which is folded into a tube with layered black linings to conceal the optical fibre bundle. Wiring LEDs with mini connectors are inserted in the belt, and closely positioned for connecting with the optical fibre bundles by snap fastening harnesses, as shown in Figure 6.32.

Figure 6.31 Concealing the optical fibre bundle by the tubular and layered design

Figure 6.32 Insertion of the wiring LED and mini connector; packaging of the optical fibre bundle and LED

The design of the man’s luminescent vest is simpler but effective. The optical fibre bundle and loose fibres are carefully bent and concealed by binding seams and extra lining fabrics, as shown in Figure 6.33. Since wires between LEDs and mini connectors are replaced by conductive fabric circuitry, fabricated and fixed between lining fabrics, LEDs and connectors are separately packaged by using fabric substrates and snap fasteners shown in Figure 6.34.

Figure 6.33 Concealing the optical fibre bundle by the binding seams and lining wrap

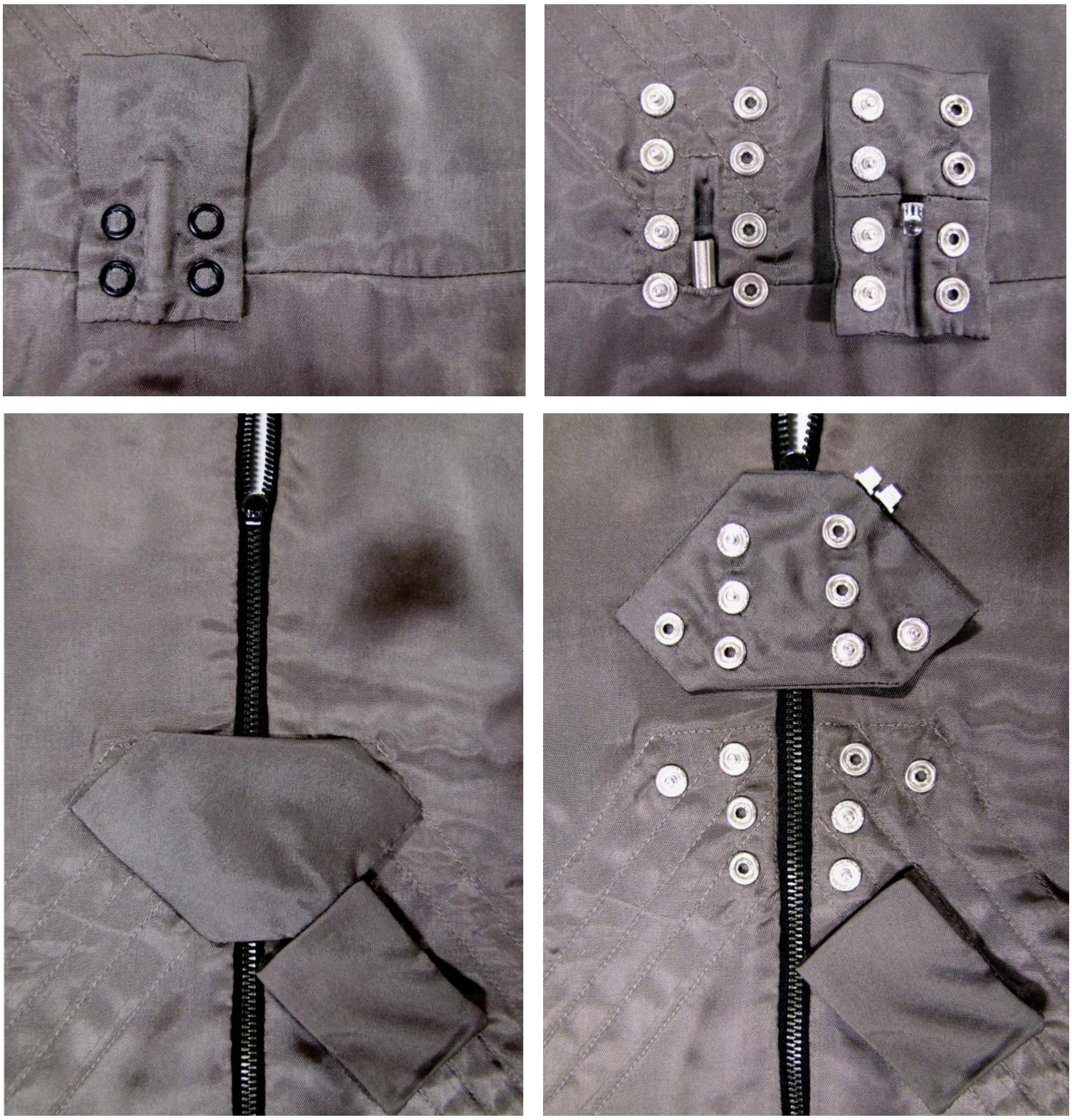


Figure 6.34 Packaging and connecting of the LED and mini connector — On and off

6.2.4 Encapsulation of the PCB and battery

The main integrated circuit board and rechargeable battery have also been encapsulated, shown in Figure 6.35, using a transparent heat-shrinkable sleeve of 31mm width and 0.25mm thickness, for sealing and protection. The microphone, plug connectors and switches are exposed from the sleeve for usage.

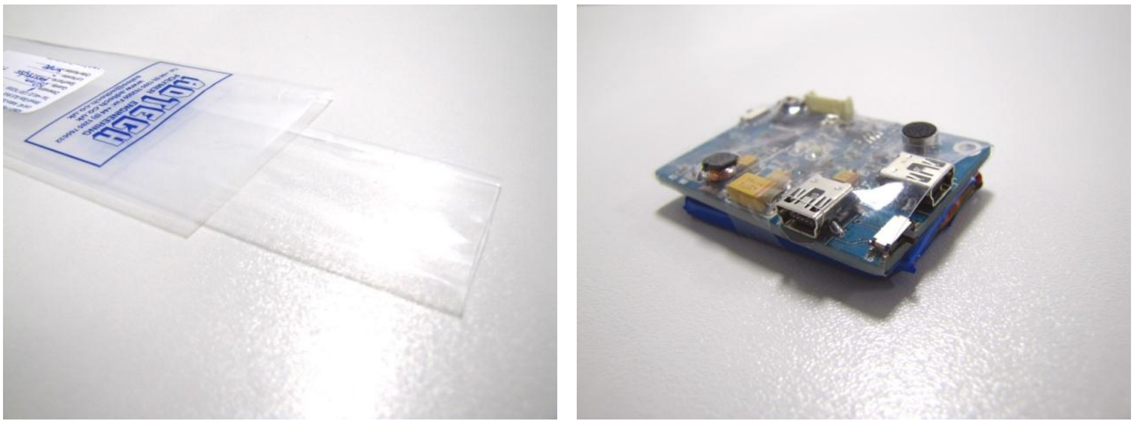


Figure 6.35 Encapsulation of the PCB and battery by a heat-shrinkable sleeve

6.2.5 Modular design

Being separately fabricated in a modular design and then used in the whole system, "modularity" provides multiple functionalities, ease of change or software updating, flexibility in design, and also attempting to combine the advantages of standardization with customization [94]. This kind of modular design is widely used in cars, buildings, computers, and in modern fashion. For example, the addition and subtraction of elements in dressing is a modular system design of the Mandarina Duck's apparel fashion range [95]. Based on this concept, our system is subdivided into smaller parts/modules. The modular implementations in this newly designed smart clothing system are the solar panels, the LEDs and plug connectors, the PCBs and batteries. Via simple connecting interfaces, all these parts are easily interchangeable by adding or removing modular components to create options, improve effectiveness and enhance the lifespan of the smart clothing.

Figure 6.36 displays the solar panel modules and PCBs working on or off the outerwear as well as with the pouch charging accessory. Energy harvesting is achieved by plugging these modules together with the "working stations" – clothes and charging pouches.

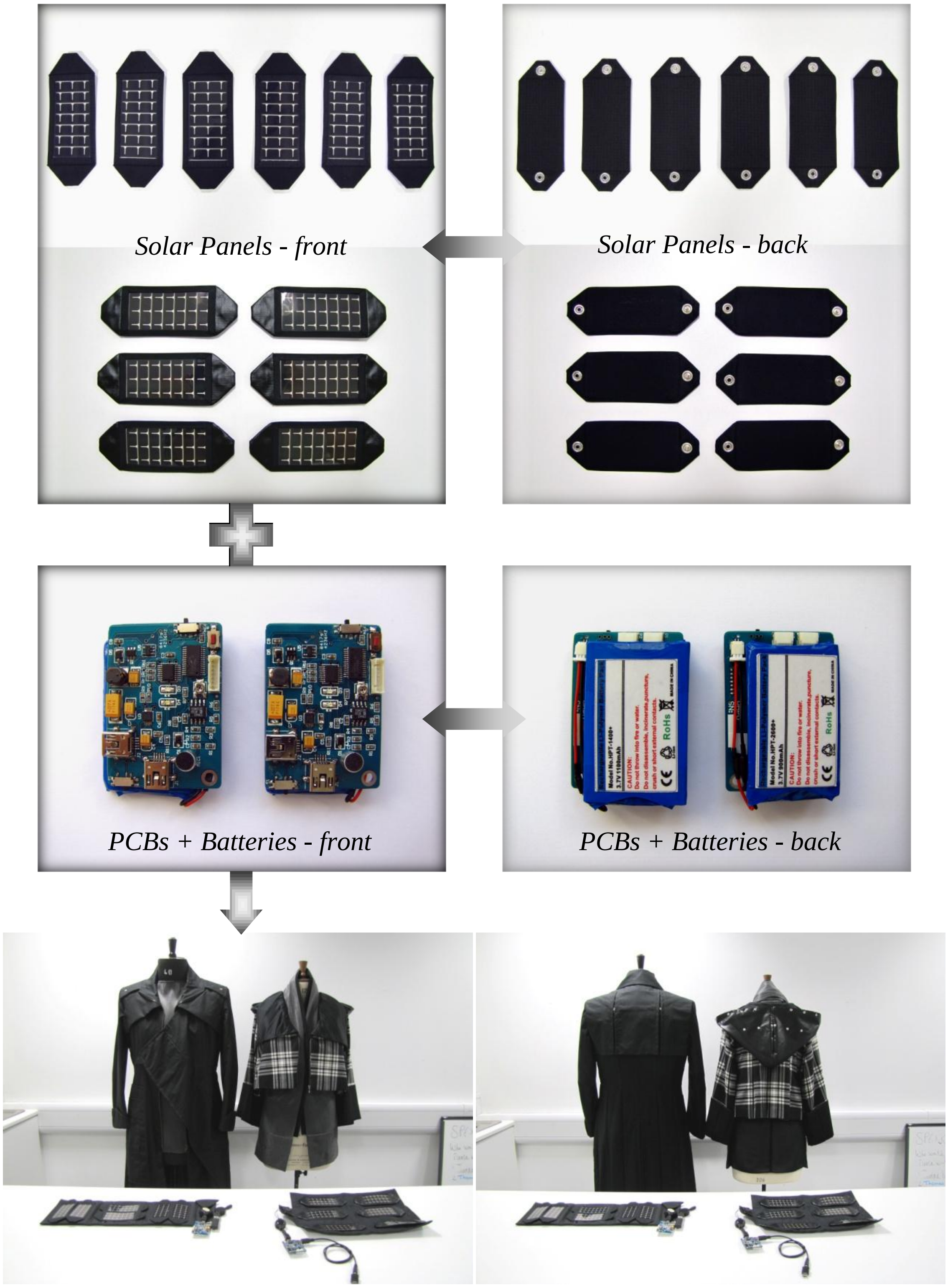


Figure 6.36 Modular designs of solar panels and PCBs – On or off the outerwear garments and charging pouches

Figure 6.37 shows an integrated belt accessory for the lady's innerwear garment, and discrete fastening modules to be attached on the man's innerwear garment, comprising of the modular LEDs and connectors, PCBs and batteries. These modules can be simply attached to activate the mood changing system at will.

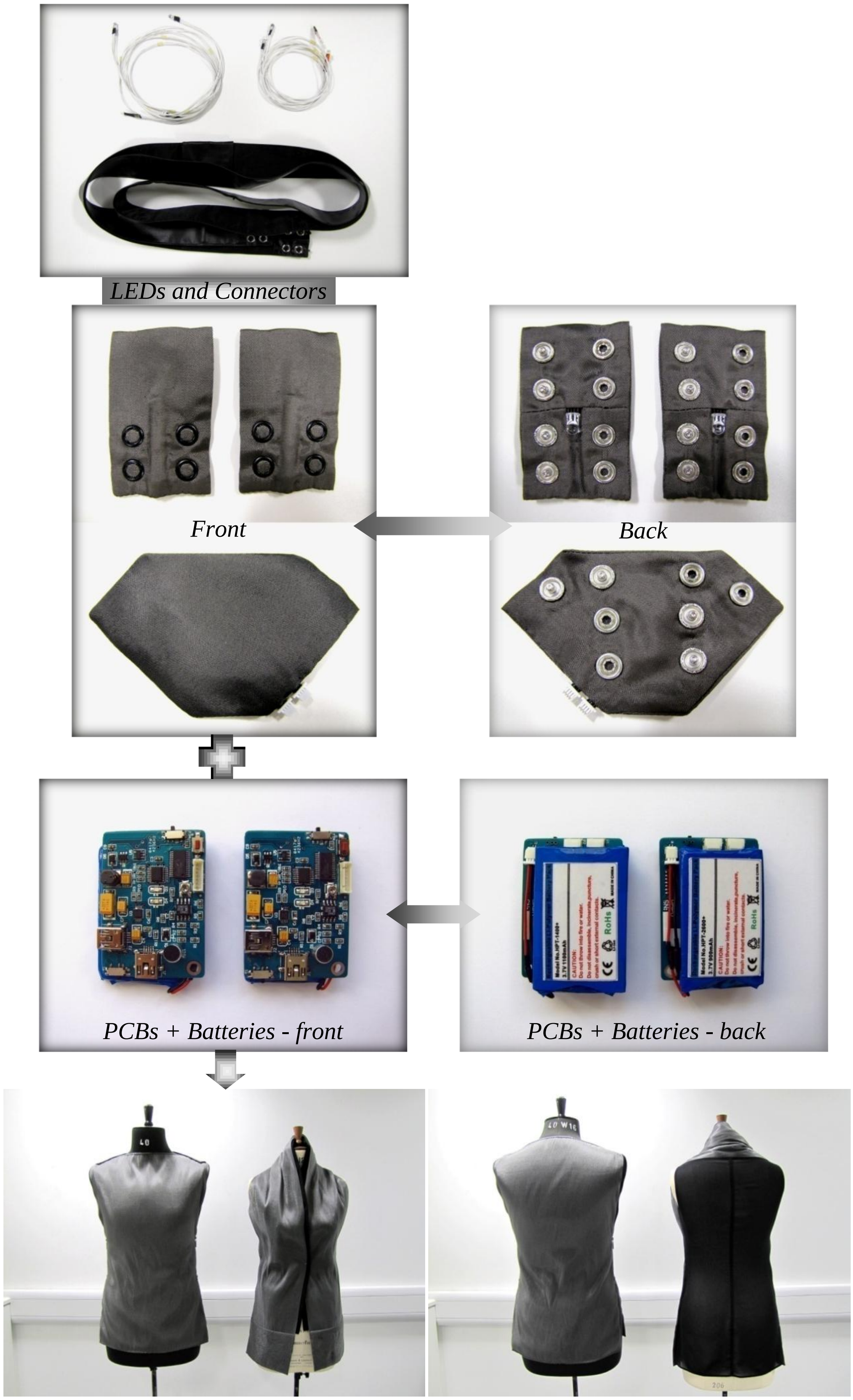


Figure 6.37 Modular designs of LEDs, connectors and PCBs – On or off the innerwear garments

6.3 Component and Garment Fitting

With the completion of fabrication design and packaging techniques, every component is made and standardized as an accessory and is now ready to fit to the whole clothing system. Fitting in this project requires both the electrical functioning and the clothing fitting from the view point of the aesthetics. A suitable position has been found for every functional component to integrate unobtrusively with clothing. As stated in Chapter 5, outerwear and innerwear are designed separately to perform solar harvesting and mood changing functions respectively, but also combined and integrated in the smart clothing system.

6.3.1 Outerwear design with solar harvesting function

<u>Lady's jacket with hood and pockets design</u>

As shown in Figure 6.38, fabricated and packaged solar panels are fitted on the hood of the lady's jacket by detachable snap fasteners. A PCB with the rechargeable battery and a mobile phone can be placed in the front pocket as shown in Figure 6.39. The textile-based circuitry is laid in and secured along the seaming allowance inside the clothing layers, and terminated by the snap fasteners as shown in Figure 6.40.

Figure 6.38 Fitting solar panels on the hood of the lady's jacket

Figure 6.39 Positioning PCB and mobile phone in the front pockets of the lady's jacket

Figure 6.40 Fitting textile-based circuitry inside the lady's jacket by secured insertion and fastening connection – Outside and inside, P=Positive, N=Negative

<u>Man's coat with yoke and pockets design</u>

Figure 6.41 shows the fitting of solar panels on the yoke of the man's coat with embedded fabric circuitry and detachable fastening connections. The front patch pocket in Figure 6.42 and the concealed pocket in Figure 6.43 are made as replaceable charging ports corresponding to the installation of the PCB with battery and electrical devices.

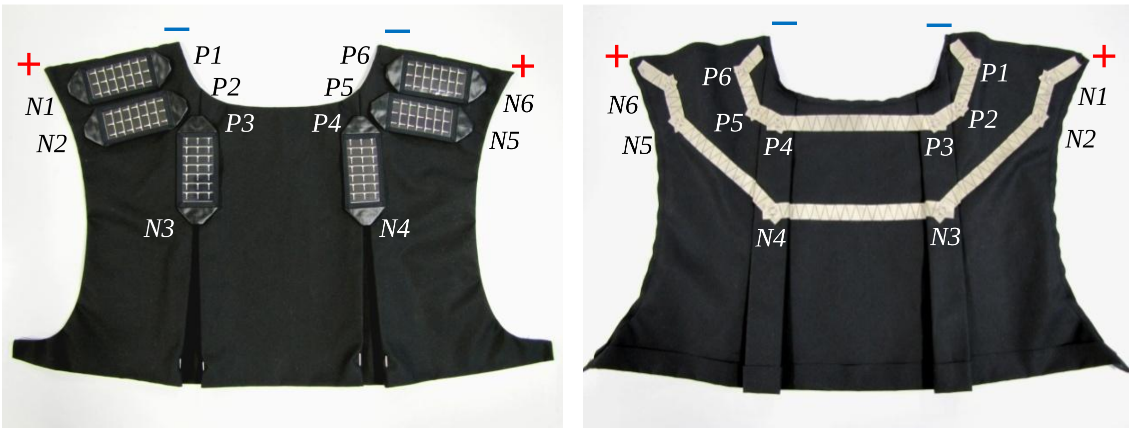


Figure 6.41 Fitting solar panels on the yoke of the man's coat – Outside and inside, P=Positive, N=Negative

Figure 6.42 Front patch pocket (right side of the man's coat) as the first charging port

Figure 6.43 Front concealed pocket (left side of the man's coat) as the second charging port

6.3.2 Innerwear with mood changing function

<u>Lady's vest with belt and pocket design</u>

The lady's innerwear is designed as a detachable layer top as a one-piece luminescent fabric shaped as a scarf, providing elegance and variation of form, as shown in Figure 6.44. Figure 6.45 shows two LEDs connected with mini connectors by wiring circuitry through the accessorized belt. The encapsulated PCB and battery are then installed in a small pocket along the belt to connect with these mini connectors, as shown in Figures 6.46. The microphone is positioned to the outside hole of the pocket, sensing the wearer's voice.

Figure 6.44 One-piece lady's luminescent garment with the belt accessory and wiring circuitry – Outside and inside

Figure 6.45 Wiring connection for the LEDs and mini connectors

Figure 6.46 Installation and connection of the PCB and battery in a small pocket

<u>Man's vest with pocket design</u>

As a simple design, the man's innerwear is improved and shaped into two detachable pieces of luminescent fabric, shown in Figure 6.47 with its textile-based circuitry. The conductive fabric strips are carefully planned according to the colour corresponding with the LED leads, and skilfully inserted between the lining fabrics as shown in Figure 6.48. To fit the fibre-optic bundles and the PCB on the clothing, LEDs and mini connectors are designed and made as detachable accessories by fastening connections, as shown in Figure 6.49. Figure 6.50 shows a foldable pocket on the garment along the circuitry for attaching the PCB.

Figure 6.47 Two pieces man's luminescent garment with the lining design and textile-based circuitry – Outside and inside

Figure 6.48 The circuitry made by conductive fabrics and inserted between the lining fabrics

Figure 6.49 Detachable LEDs and connectors with the man's luminescent garment

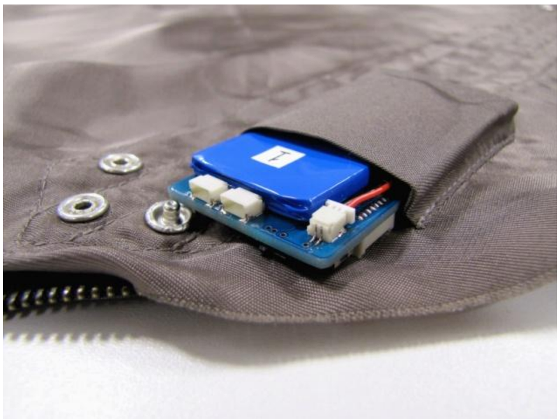


Figure 6.50 Installation of the PCB and position of the microphone in the designed pocket

Aesthetic appearance and fitting of the clothing have been considered, every component is well connected and tested. Energy harvesting and mood changing functions have been tested successfully and integrated to the whole SMART clothing system.

CHAPTER 7 – OPERATION OF THE SMART CLOTHING SYSTEM; ENERGY HARVESTING AND MOOD CHANGING

In this project, solar harvesting and sound sensing are inputs for energy and mood, whilst power consumption for electronic devices and colour changing through lighting are the corresponding outputs. Between each set of input and output, there are key steps in processing, computing and testing which determine the working of the system. Purposed printed-circuit boards (PCBs) are designed and made by integrating, programming and implementing ICs. For the energy system, a PCB is required for storing and conditioning the power from the PVs. Another circuit consists of a transducer and a programmable microcontroller used to decode the wearer's mood intelligibly through a microphone in the information system. In this chapter, how the actual SMART clothing system works from energy harvesting to mood changing will be described through experimental work on the clothes, the collection of which will finally be presented.

7.1 System Operation

Before two functional circuits are integrated into one PCB, the experimental and developmental processes are carried out in several phases for each system design for ensuring practical and efficient circuits to be integrated into the clothes. In these processes, a careful test plan by examining the electronics in a Testing Circuit Board (TCB) before moving to the final Printed Circuit Board (PCB) has been carried out. The layout of the PCB is based on microchip technology and miniature components as much as possible. TCB was made on the bench with test circuitry by wring and soldering to consider the most feasible and optimum circuit design. Without a testing plan, the results can be adversely affected by inefficiencies, sacrificing reliability. Therefore, careful planning in TCB has avoided drawbacks and has addressed early problems of size, functionality and adjustment before the final PCB design process. The technology implementation of the PCB with other components presented on/in the clothes was also tried and tested. The electronic process of creating the PV charging and LED lighting systems are carried out with the assistance of electronic expertise.

7.1.1 The solar harvesting system

<u>Phase 1 — Solar charging TCB</u>

At the first stage of connecting the PV modules to a PV array in parallel and combined circuits, electric charging was achieved but was not stable in direct sunlight. Figure 7.1 demonstrates this with the mobile charging indicator (*in charge*).

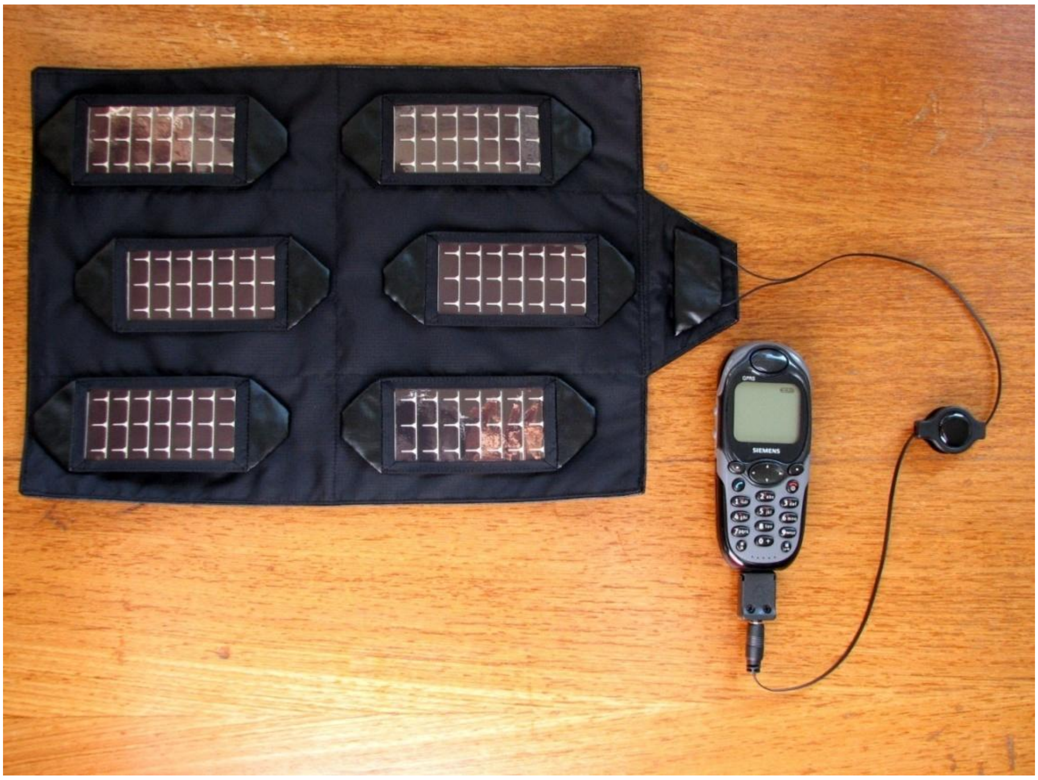


Figure 7.1 Mobile charging by the PV array directly

As discussed in Chapter 3, the operating current of the PV array is 66mA in the combined circuit, and 132mA in the parallel circuit. Consequently, the electric charging state of the PV array was unstable in the combined circuit sequence than in the parallel circuit sequence, due to a lower current capacity. To charge a mobile phone at 500mA or above, the direct charging efficiency by the PV system was restricted by weather conditions and was affected by inconsistent sunlight. Therefore, the charging time is unexpectedly increased due to a change of weather from sunny to cloudy. These trials have proved modest conversion efficiency and intermittent solar harvesting when compared with a stationary power supply.

For using solar energy rationally and effectively, a solar charging controller with power storage needed to be considered. A solar charging circuit capable of recharging a battery was to be designed and made. The type of battery was based on the power consumption of the system — lighting up the LEDs of the luminescent clothes and charging the portable electronic devices. A lithium type battery of 4.2V, 300mA capacity and 20mm × 30.5mm × 6mm in size was found most suitable. Figure 7.2 shows the primary TCB experiment of the PV array capable of charging this lithium battery. Experimental PV modules with the same capacity as the PV films were used at this experimental phase.

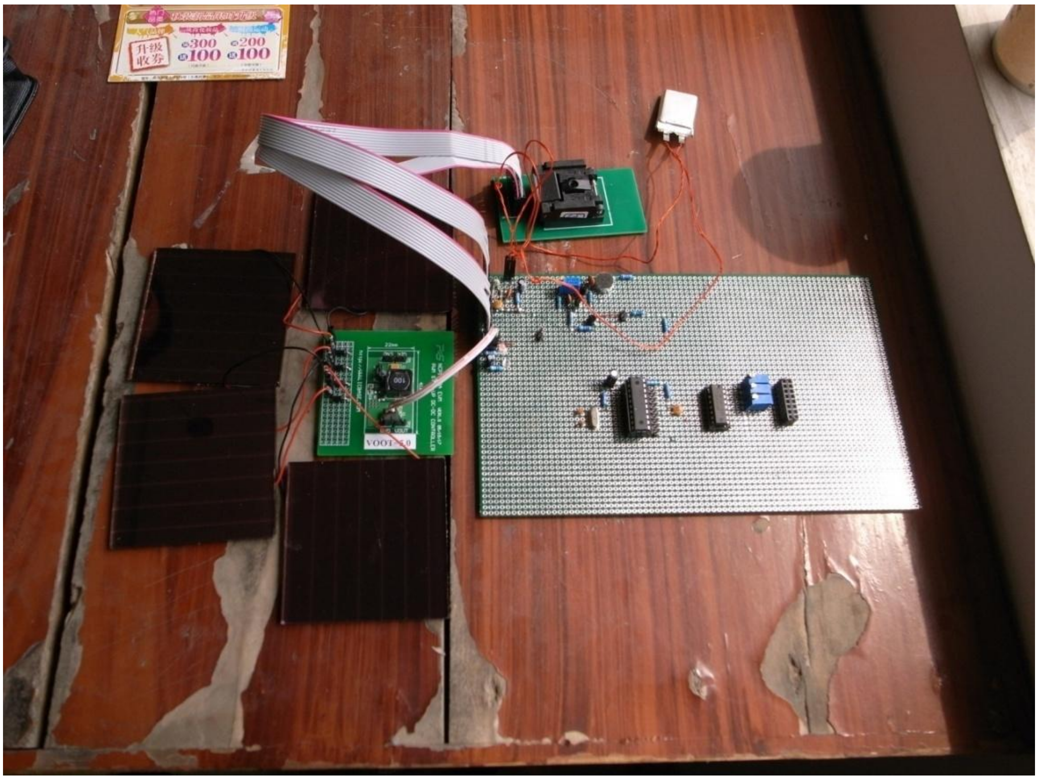


Figure 7.2 The primary solar charging TCB with a rechargeable lithium battery

<u>Phase 2 — Solar charging TCB and PCB</u>

After primary TCB experiments, the optimum TCB design was found before deciding on the final PCB size and component layout. Based on the battery's dimension, the size of the circuit board was reduced to be smaller than half the size of a credit card by using smaller electronic components, as shown in Figure 7.3.

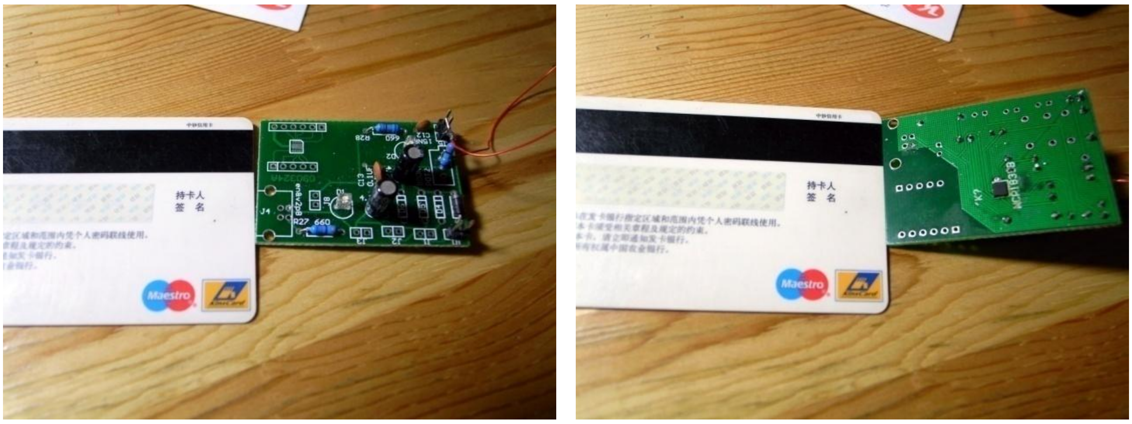


Figure 7.3 The optimum solar charging TCB – Front and rear

Furthermore, the thickness of the circuit board needed to be minimized by further miniaturising the chip components and using surface mount technologies. To realize this optimum designed PCB as illustrated in Figure 7.4, a number of factors have been taken into consideration, such as the solar charger IC, the LED indicators, connectors, switches, etc. Figure 7.5 displays the first PCB prototype based on the experimental TCBs.

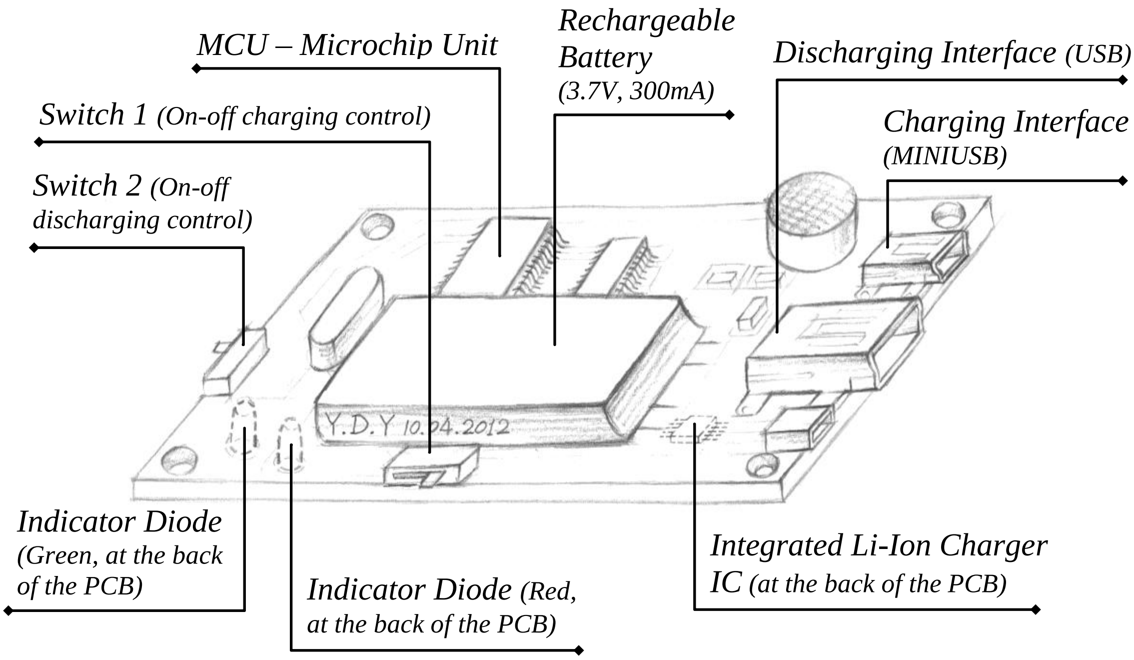


Figure 7.4 Sketch of the first PCB prototype with the main components for solar charging

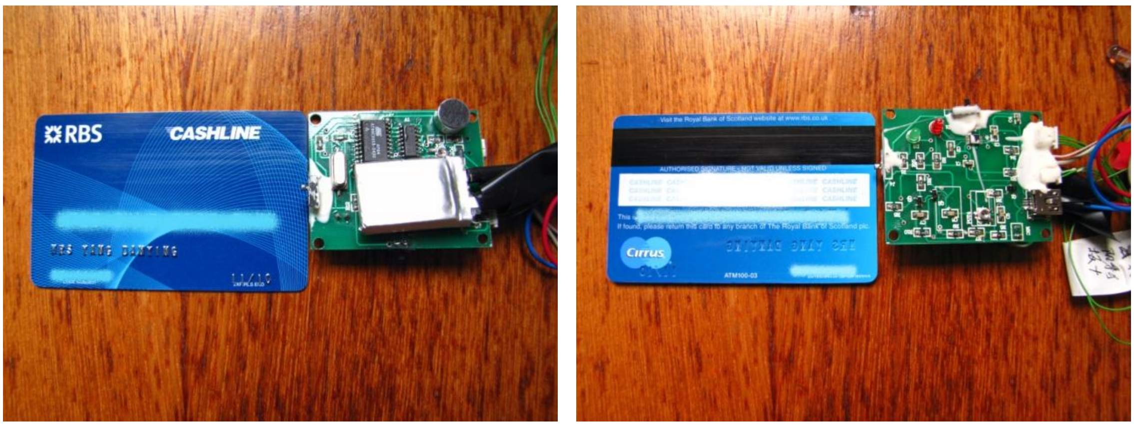


Figure 7.5 The first PCB prototype based on the experimental TCBs – Front and rear

Additionally, protective (Schottky Barrier) Diodes are required in the connection between each PV panel and the main circuit board, as stated in Chapter3. Since all PV panels are connected with one connector for linking with the PCB, every SBD is individually inserted and soldered to every single panel package, as explained in Chapter 6. Figure 7.6 shows the connection of the experimental SBDs and PV panels on the TCB, and Figure 7.7 shows the insertion of the miniature SBDs in the PV panels' packaging.

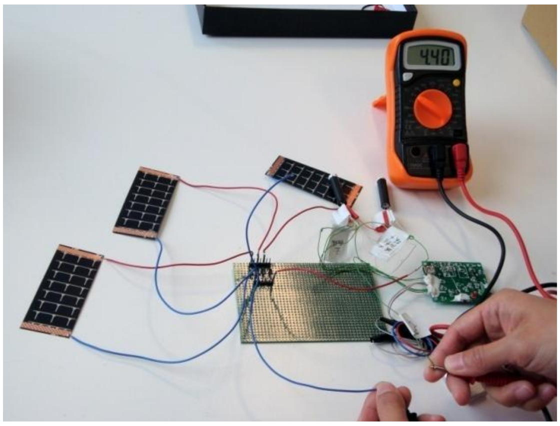


Figure 7.6 The connection of the experimental SBDs and PV panels on the TCB

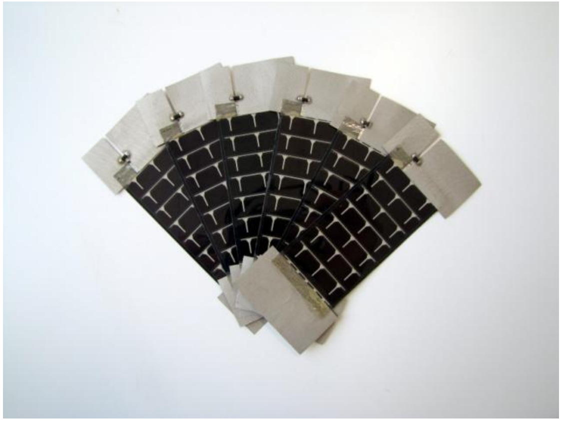


Figure 7.7 The insertion of the miniature SBDs in the PV panels' packaging

Energy harvesting and power storing are then obtained and controlled, shown by green/red indicator lights, as seen in Figure 7.8 and 7.9. Red LED shows charging error; green LED shows charging status – on state is in charging, off state is fully charged, as stated in Chapter 3. The mains power supply and PV system were both experimentally tested to charge the battery (3.7V, 300mA) via the first PCB prototype and the results are shown in Table 7.1. The results of the PV charging system are still somehow variable due to weather conditions but controllable.

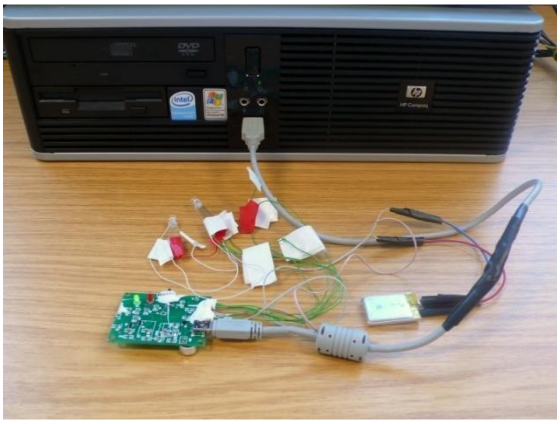


Figure 7.8 Charging by the stationary PC power supply

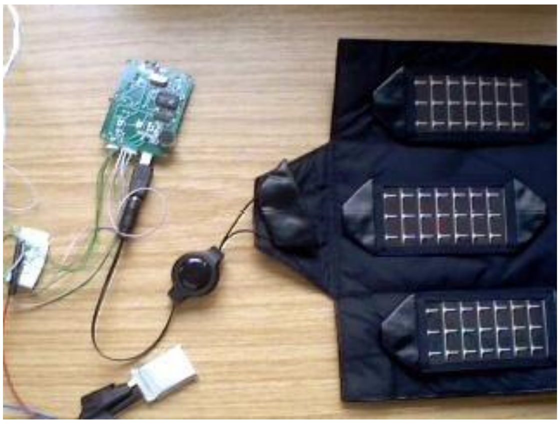


Figure 7.9 Charging by the portable PV array

Charging System	Operating Voltage (V)	Operating Current (mA)	Practical Charging Time (hr. /min.)
Stationary PC	5	500	00.45
Portable PV array	4.2	100~130	02.30~03.40

Table 7.1 Charging results for the PCB with the battery of 3.7V, 300mA through two power sources

<u>Phase 3 — Mobile phone charging TCB and PCB</u>

In testing of the first PCB prototype, the fully charged battery (3.7V, 300mA) successfully lit up two RGB LEDs of 3.6V, 30mA per unit, and permanently ran for more than 2.5 hours. However, the charging of other portable electronic devices was unattainable, because of the low battery capacity. For example, the capacity of a standard mobile phone's battery is 3.7V at 500mA or above, which means that the 300mA battery is not sufficient to perform further charging functions. The energy utilization is therefore reconsidered in relation with the mobile phone charging circuit design for higher current and boosted voltage, as explained in Chapter 3. Figure 7.10 shows the mobile phone charging TCB.

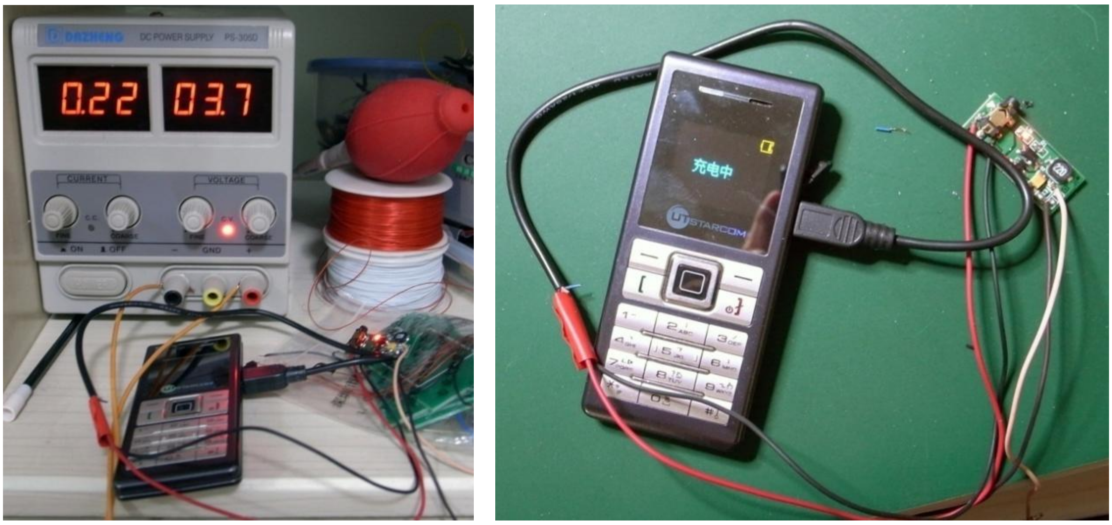


Figure 7.10 Mobile phone charging TCB with the voltage boost converter design

As is well known, the larger the capacity of the battery, the bigger the size of the battery. To keep with the PCB's physical size but enhancing the functional usage of the system became a challenging problem in this project. Figure 7.12 displays successful mobile phone charging from the final PCB prototype as illustrated in Figure 7.11, with a compact rechargeable battery of 3.7V at 900mA whilst keeping the battery size as small as the size of the PCB.

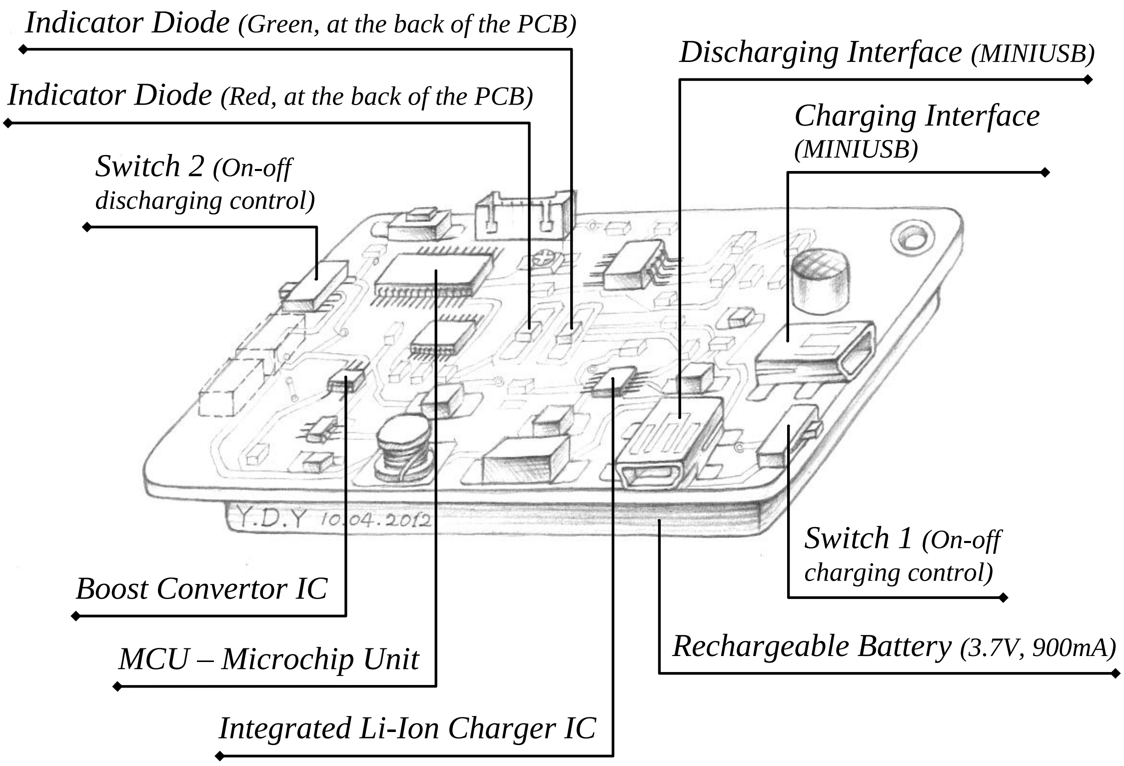


Figure 7.11 Sketch of the final PCB prototype with the main components for mobile phone charging

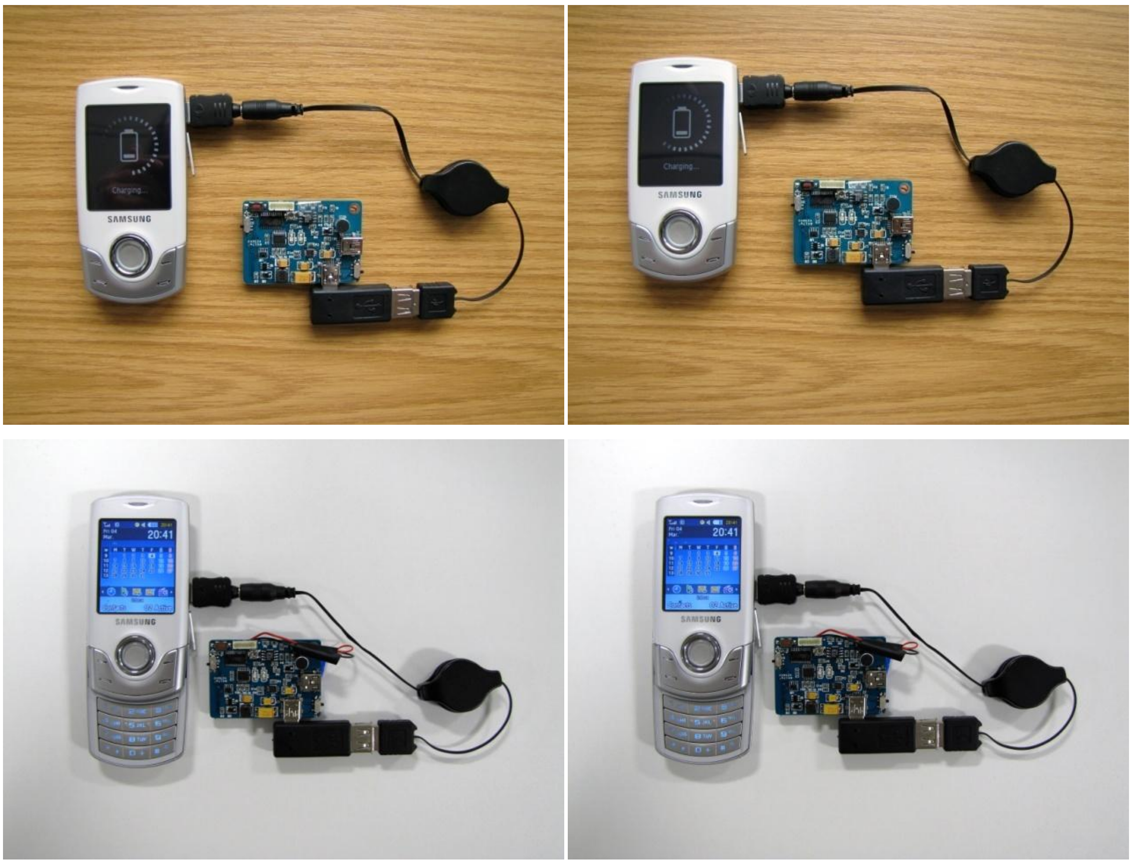


Figure 7.12 The final PCB prototype with the mobile phone charging circuit

The charging result for the mobile phone with the 3.7V, 850mA battery is compared with the mains power supply as shown in Table 7.2. In the meantime, recharging of the final PCB with the 3.7V, 900mA battery was also undertaken by the PV system and compared with the mains power supply, shown in Table 7.3.

Power Sources	**Operating Voltage (V)**	**Operating Current (mA)**	**Practical Charging Time (hr. /min.)**
Stationary PC	5	500	02.00
PCB and the rechargeable battery (3.7V, 900mA)	5	666	01.32

Table 7.2 Charging results for the mobile phone with the battery of 3.7V, 900mA through different power sources

Power Sources	**Operating Voltage (V)**	**Operating Current (mA)**	**Battery Current (mA)**	**Practical Charging Time (hr. /min.)**
Stationary PC	5	500	900	02.10
Portable PV array	4.2	100~130	900	06.50~10.45

Table 7.3 Recharging results for the PCB with the battery of 3.7V, 900mA through two power sources

7.1.2 The smart mood changing system

<u>Phase 1 — Sound controlling and LED lighting TCB</u>

Having established the technology for accumulating and storing solar energy, the special function of the newly designed SMART clothing of sensing and changing the wearer's mood through change of colours has been achieved. As stated in Chapter 3, a microphone is used as the mood sensing transducer by detecting sound signals, while LEDs and optical fibres are applied to present colour changes, by transferring the stored electric power to light. These input and output capabilities were achieved by a newly developed micro controlling circuit.

With the chosen LEDs needing maximum 3.6V, 30mA for lighting, the TCB in Figure 7.13 was constructed and tested by detecting the sound signals and converting them to electrical signals through a microphone and then programming the microchip and microprocessor to send the appropriate electronic signals to the LEDs for colour change and illumination.

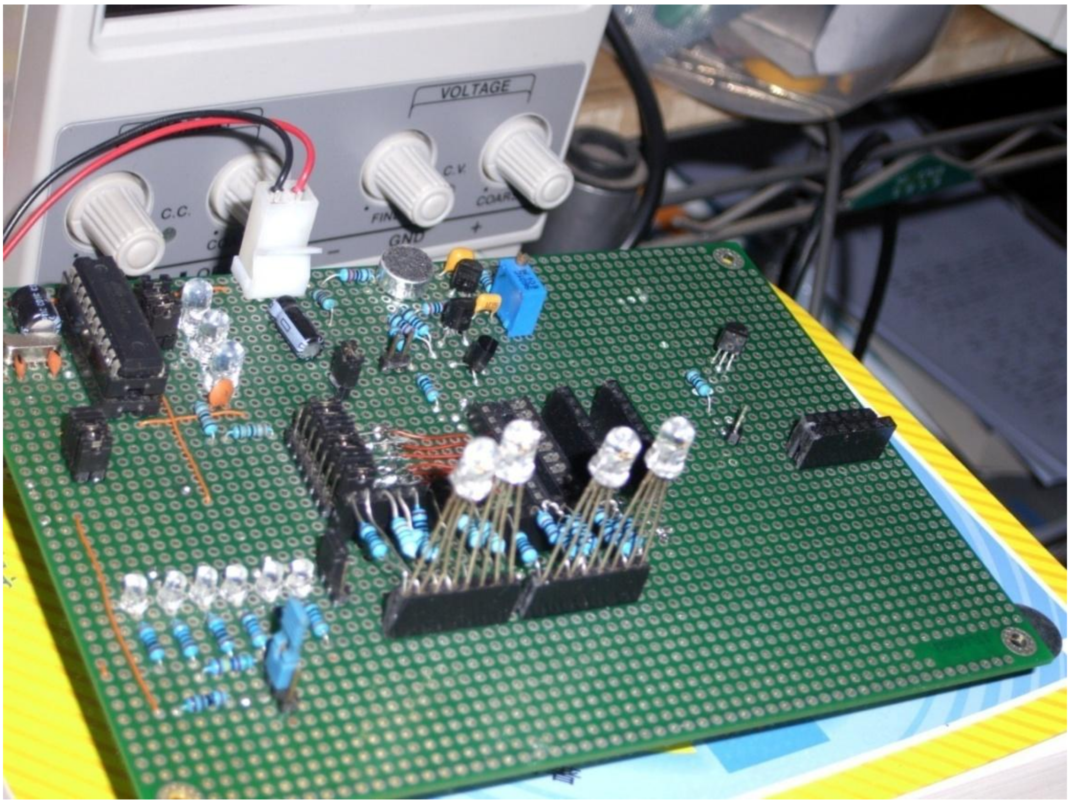
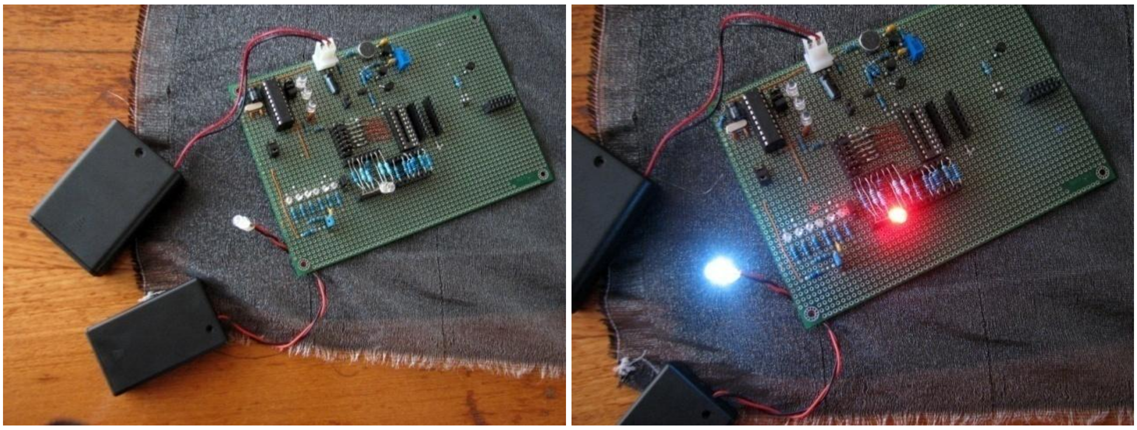


Figure 7.13 Sound controlling and LED lighting TCB

Based on the red, green and blue colour LEDs, more colours can be blended and controlled by the microprocessor according to different sound waves. Figure 7.14 shows changeable LED colours induced by sound and comparing with the non sound-activated LED of white light. At this stage, colour blending became challenging and required repeated adjustment.



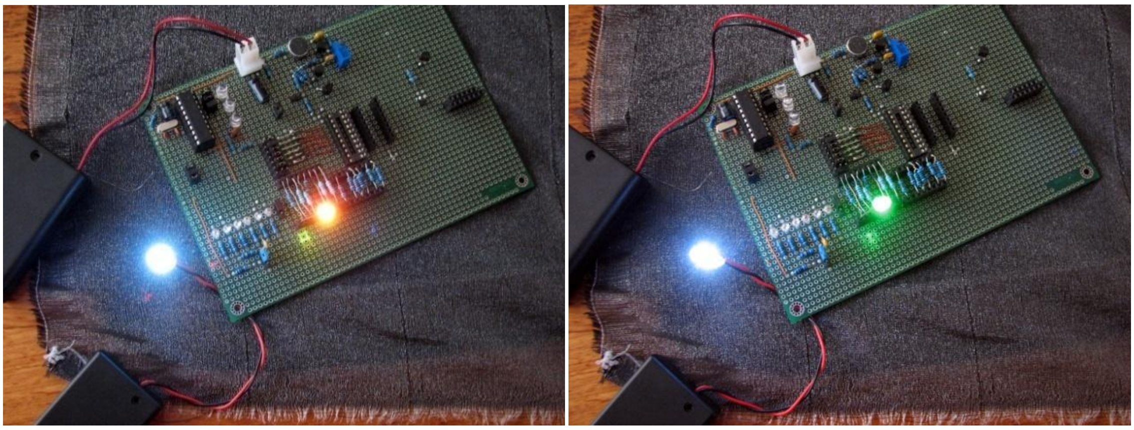


Figure 7.14 Sound-controlling LED with changeable colours, comparing with non sound-activated LED with white colour

Phase 2 — Sound controlling and colour changing PCB

After TCB testing and adjustment, devising of all the appropriate components for sound control and LED lighting in a PCB was considered, such as; microchips, microcontrollers and other miniature components, as illustrated in Figure 7.15. This PCB is integrated with the solar charging PCB and the first prototype is shown in Figure 7.16. The sensitivity of the sound was investigated at this stage.

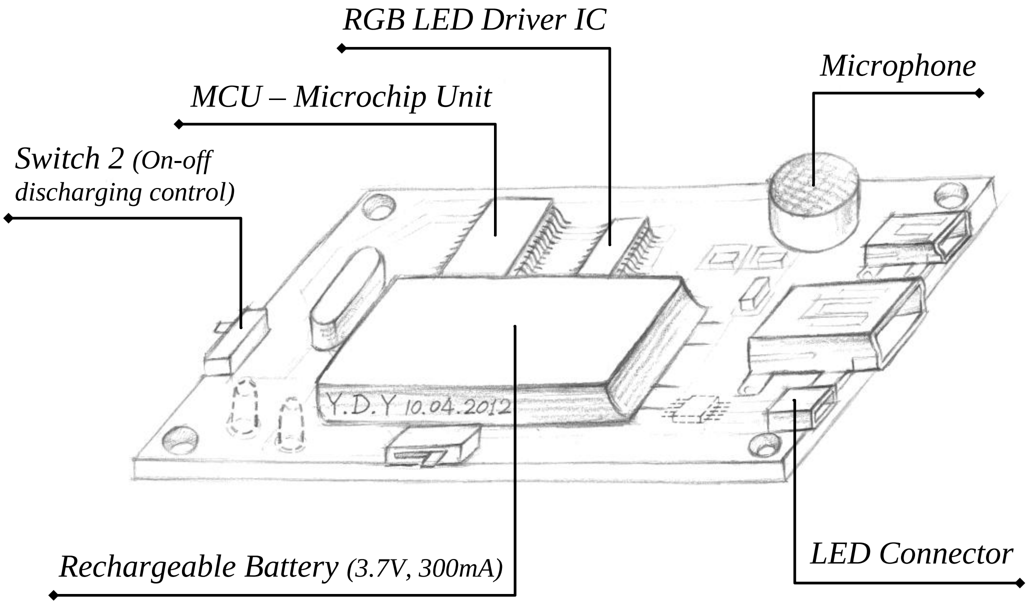


Figure 7.15 Sketch of the first PCB prototype with the main components for sound controlling and colour changing

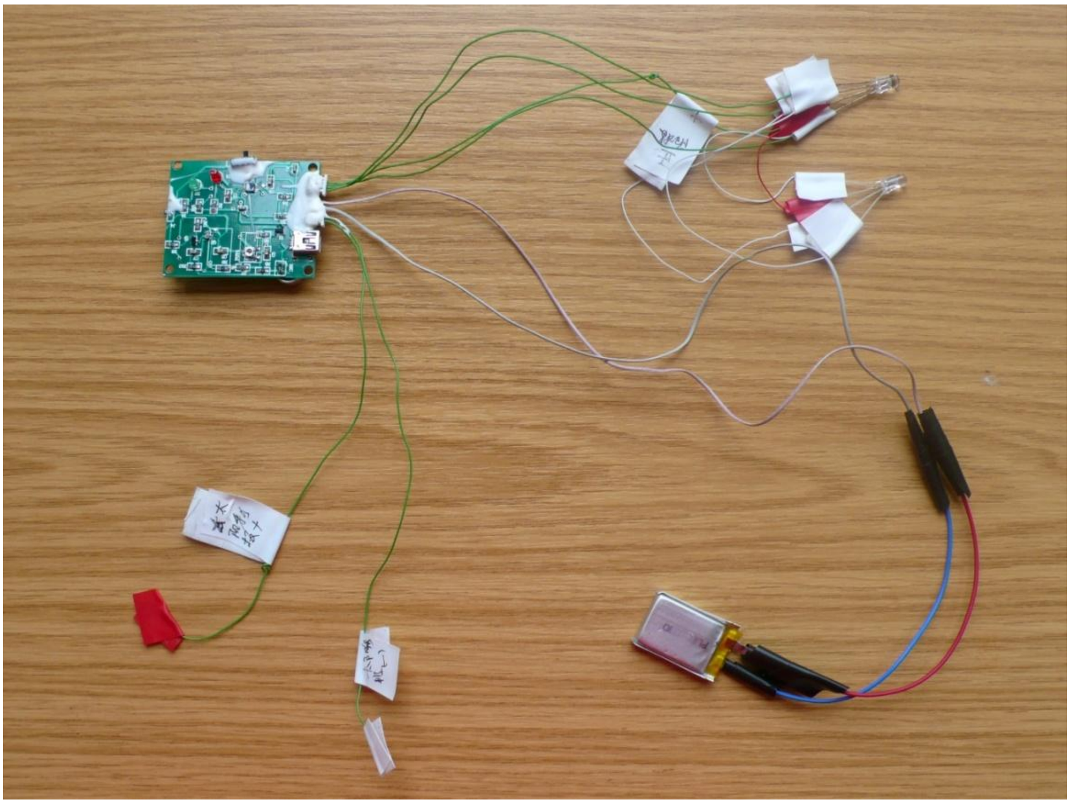


Figure 7.16 The first PCB prototype of sound controlling and colour changing circuit integrated with the solar charging circuit

LED lighting and colour change performance were tested by sound control, and compared with non sound-activated LEDs of white light, as shown in Figures 7.17 and 7.18. According to the lighting colour plan established in Chapter 4 and shown in Table 7.4, sound signals are picked up by the microphone and programmed so that they induce the voltage change from 0mV to 50mV. The voltage signals are amplified by the microprocessor and the circuit activates the LEDs corresponding to the programmed colours. For example, high sound volume triggers the red colour, and low sound volume triggers the blue colour, while between high and low volume, the output is magenta, as shown in Figure 7.17. The full RGB colour system of the programmed LEDs was developed as shown in Figure 7.18 according to volume changing of the sound, underpinned by psychological considerations, as discussed in Chapter 3.

Sound Volume	Voltage (mV)	Colour Changing			
Halt	0		Black	0 0 0	#000000
Low	7.14		Blue	0 0 255	#0000FF
Low to Moderate	14.28		Cyan	0 255 255	#00FFFF
Moderate	21.42		Green	0 255 0	#00FF00
Moderate to High	28.56		Yellow	255 255 0	#FFFF00
High	35.7		Red	255 0 0	#FF0000
High to Low	42.84		Magenta	255 0 255	#FF00FF
Tutti	50		White	255 255 255	#FFFFFF

Table 7.4 RGB LED colour changing design – 8 Colours Plan

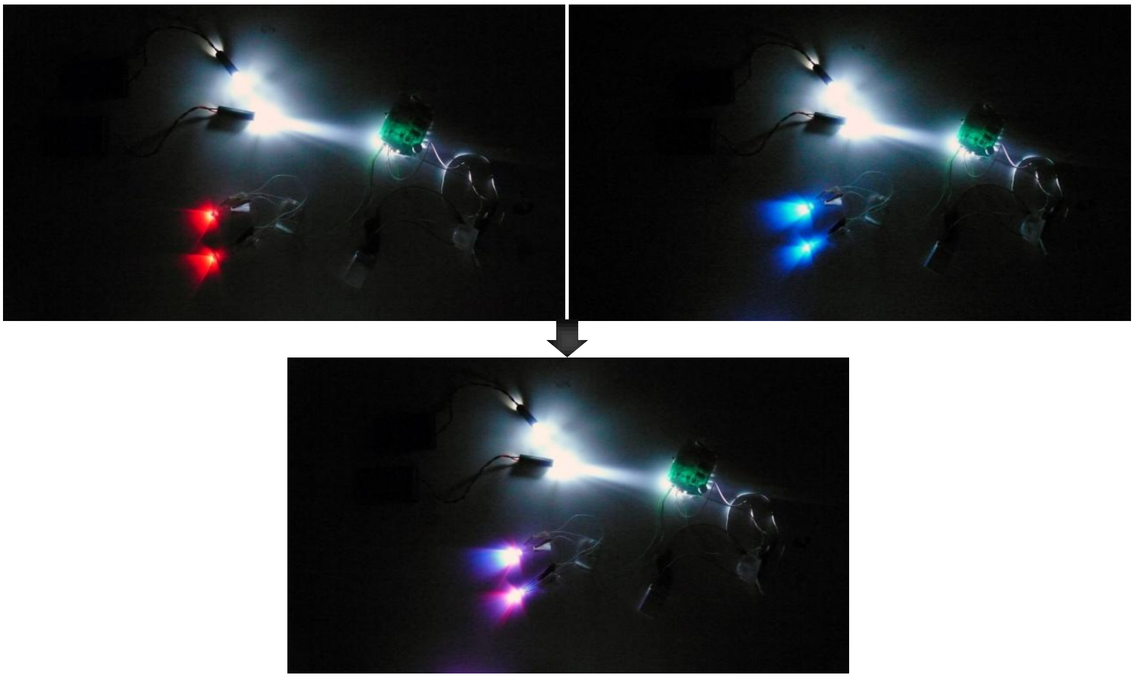


Figure 7.17 LED lighting and colour changing performance of the first PCB prototype – From R to B

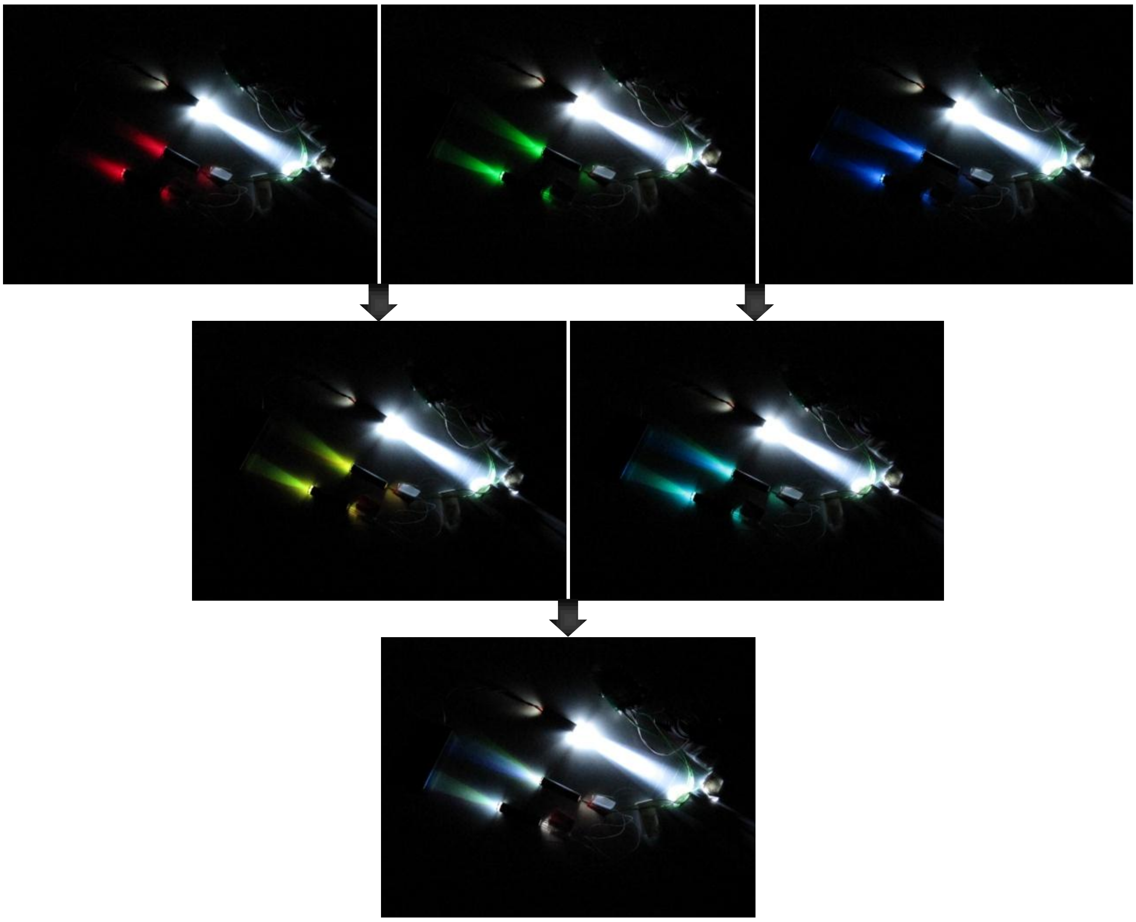


Figure 7.18 LED lighting and colour changing performance of the first PCB prototype – RGB

There was one problem raised in the presentation of the first PCB prototype when the LEDs were connected with the luminescent fabrics. Under control experiments, the luminous intensity of the programmed RGB LEDs was much lower than the single white LED, which caused a faded visibility of the fibre-optic fabric, as seen in Figure 7.19.

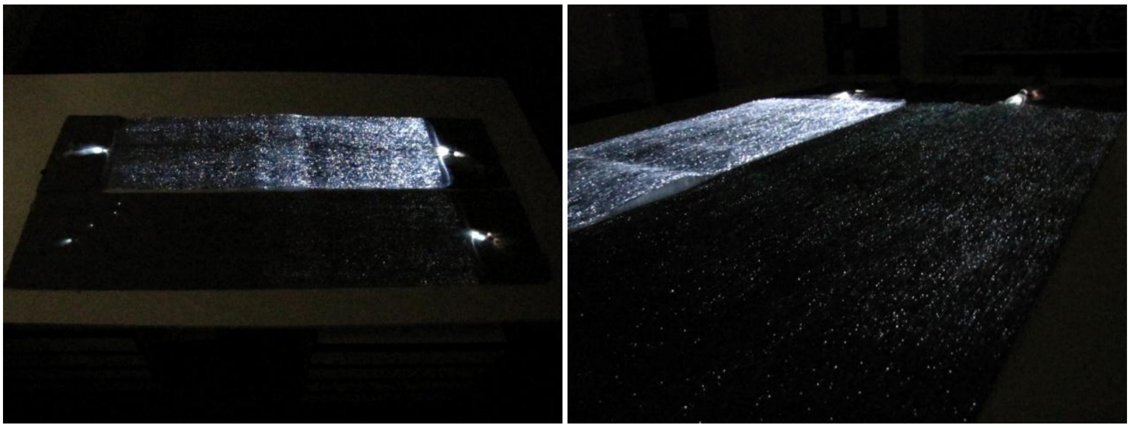


Figure 7.19 Luminous intensity of the sound-controlling RGB LED, comparing with the non sound-activated white LED, through the fibre-optic fabrics

Phase 3 — LED lighting and colour changing PCB

In order to solve the luminous problem which occurred in the first PCB prototype, superbright LEDs were investigated. Accordingly, the maximum output current to LEDs was increased from 30mA to 40mA. Although 40mA is beyond those LED's typical nominal current, the flashing colour changing by the sound control limits any damage to these LEDs, i.e. they are working slightly higher than their full capacity when they are not on continuously (flashing).

With the increased current, investigating the luminous intensity was carried out on the modified PCB as shown in Figures 7.20 and 7.21. Compared with the non sound-activated LED lighting, single colour ultrabright LEDs were programmed to change the colour intensity by sound volume changes, as presented in Figure 7.22. It should be pointed out that white LEDs with higher millicandela (MCD) up to 31000mcd are brighter than coloured LEDs.

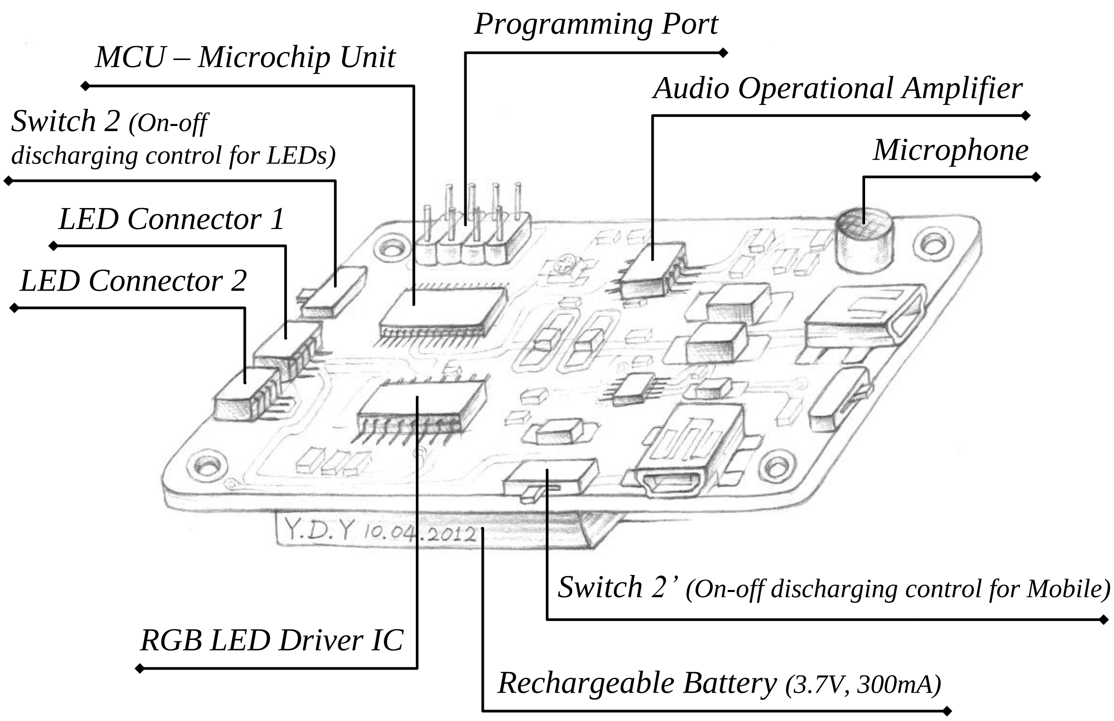


Figure 7.20 Sketch of the modified PCB prototype with the main components for sound controlling and colour changing

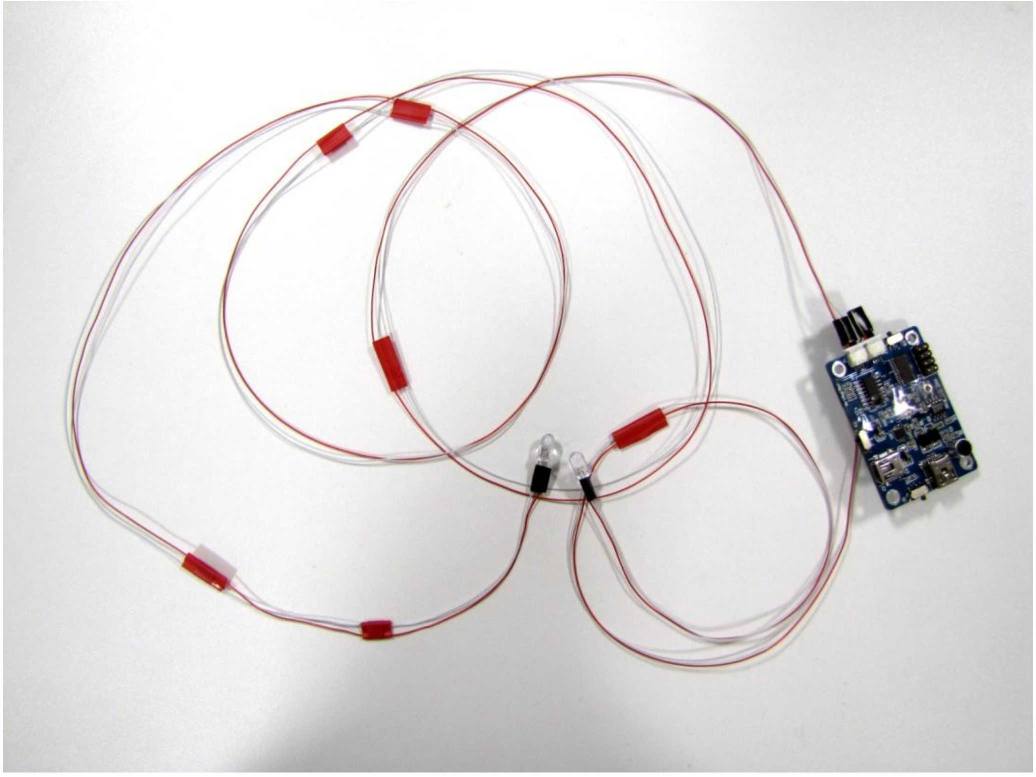


Figure 7.21 The updated PCB prototype with ultrabright white LEDs

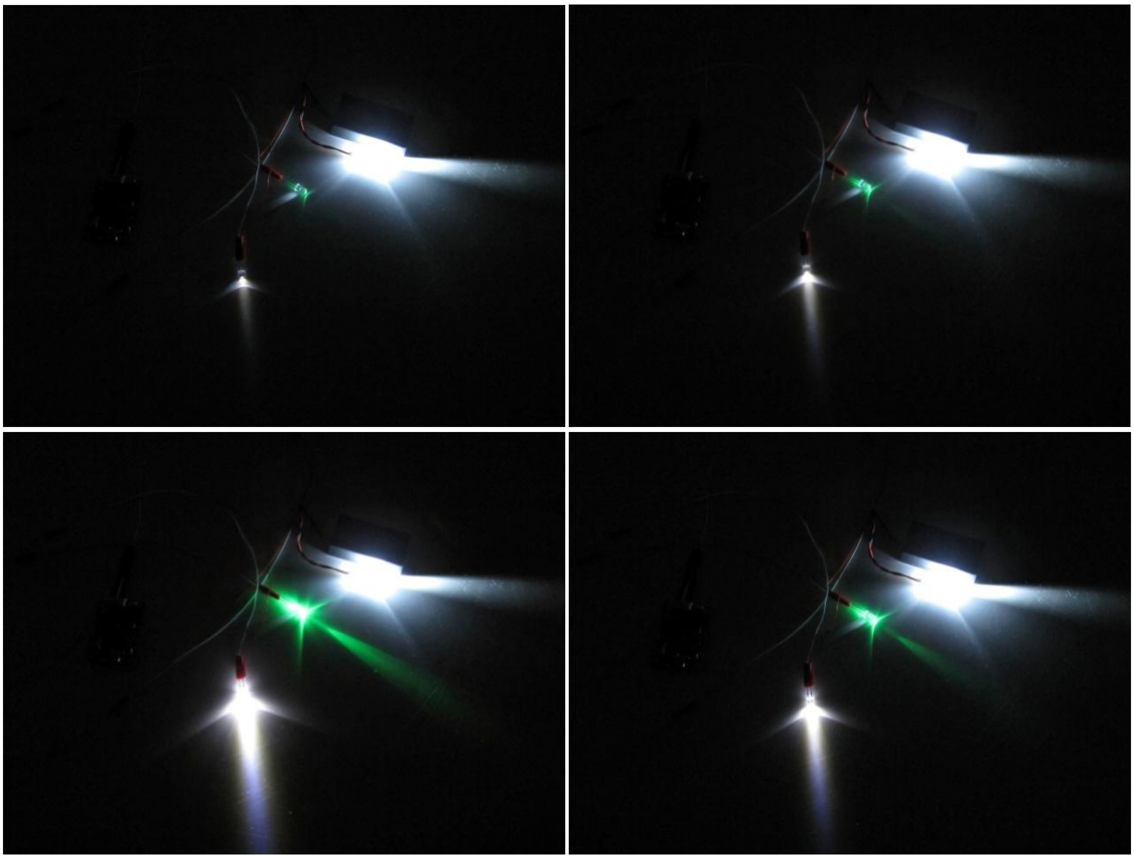


Figure 7.22 Gradual lighting changes of the ultrabright LEDs induced by sound volume changes, comparing to non sound-activated LED lighting

The PCB shown in Figures 7.23 and 7.24 is the final modified optimum circuit design to work with superbright RGB LEDs, six times brighter than the standard types; red colour 1500~2100mcd, green colour 4200~5800mcd, blue colour 1100~1500mcd, and for a total brightness of the LED up to 9400mcd at the testing current of 60mA (20mA for each chip). Specific code programming was used for designing the functionality of the touch on/off button. The touch button was positioned on the PCB to switch on the LEDs by a single push to enable the sound induced colour changing mode, as shown in Figure 7.25. Extended pushing of the on/off switch enables the LEDs to be switched to non sound-activated modes as red, green, blue or white stand alone, as shown in Figure 7.26, giving the system flexibility of use by user selection.

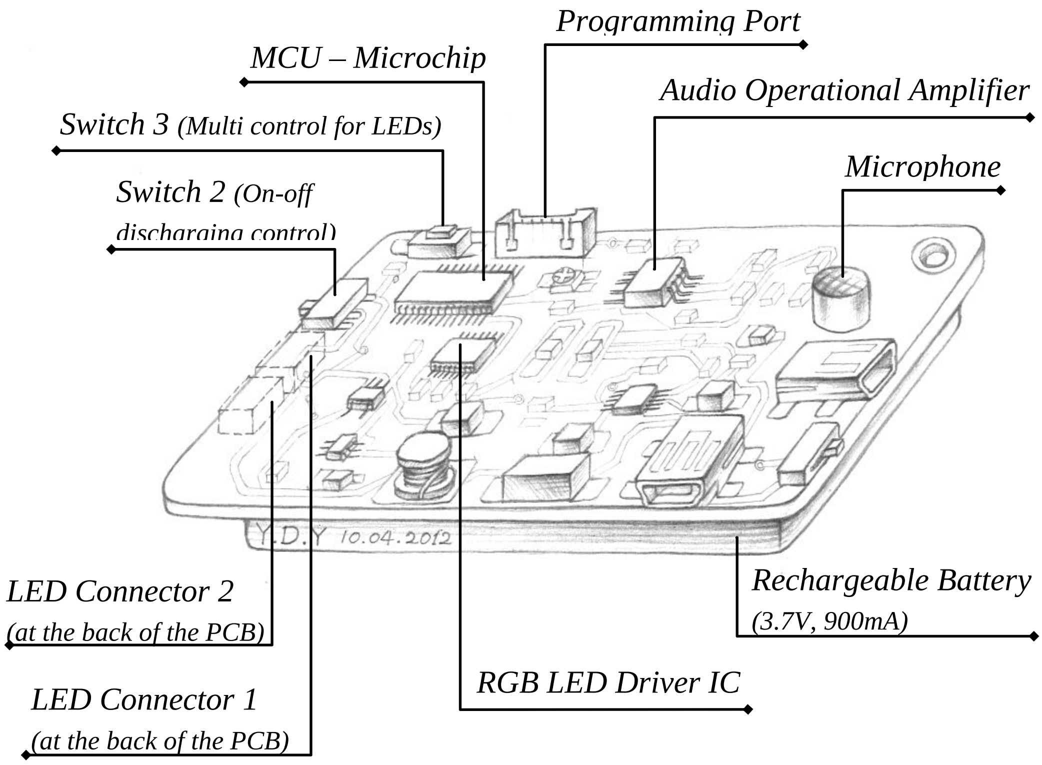


Figure 7.23 Sketch of the final PCB prototype with the main components for sound controlling and colour changing

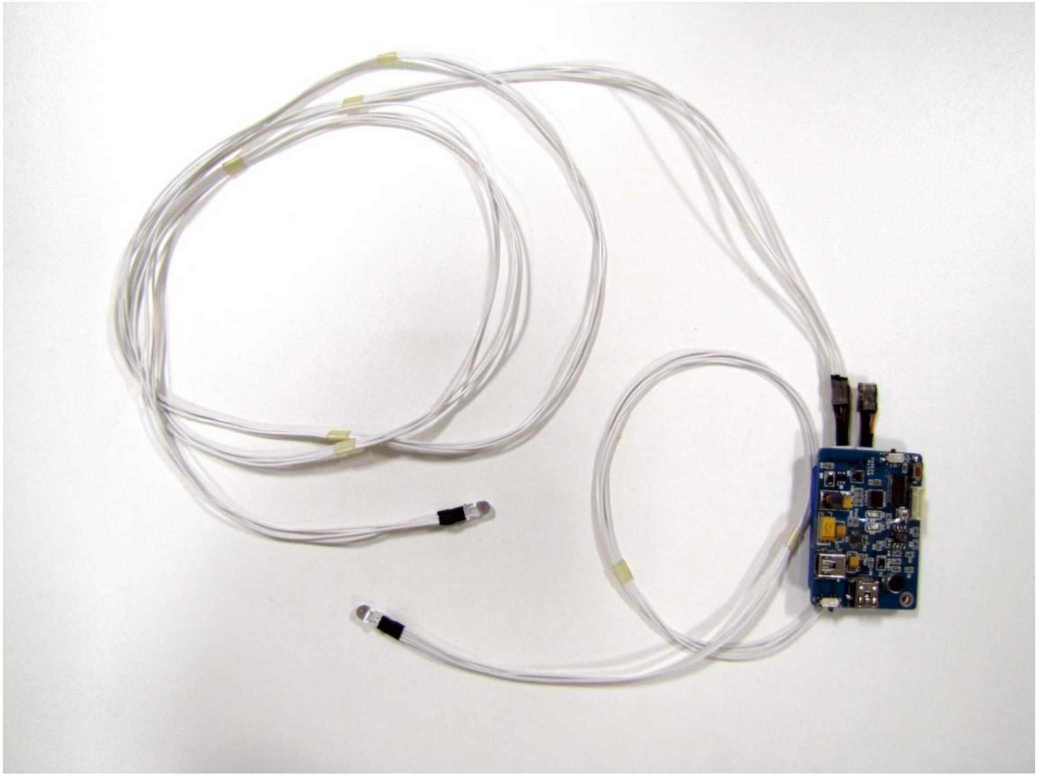


Figure 7.24 The final PCB prototype with superbright RGB LEDs

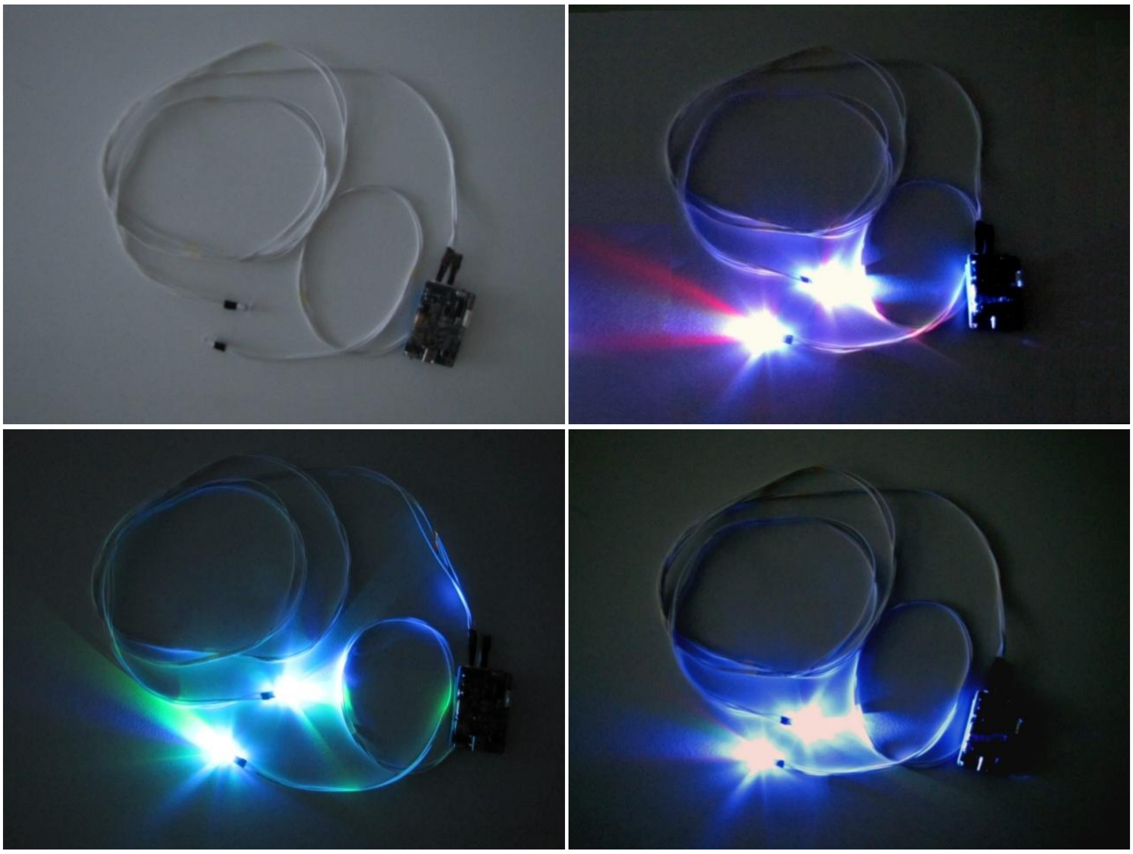


Figure 7.25 From off mode to sound-activated colour changing mode

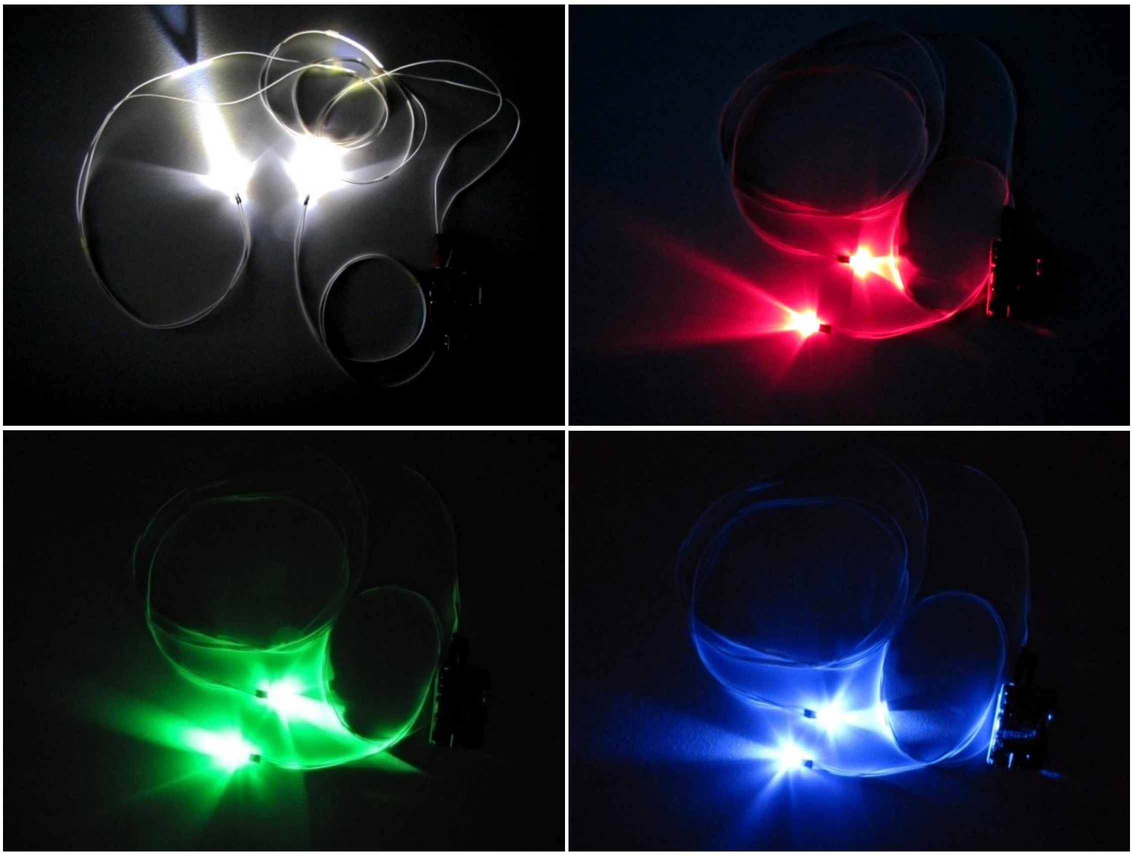


Figure 7.26 Non sound-activated modes as red, green, blue or white, manually selected

The luminescent effect of the fibre-optic fabric has consequently been optimised and enhanced at the final PCB prototype, presented in Figure 7.27.

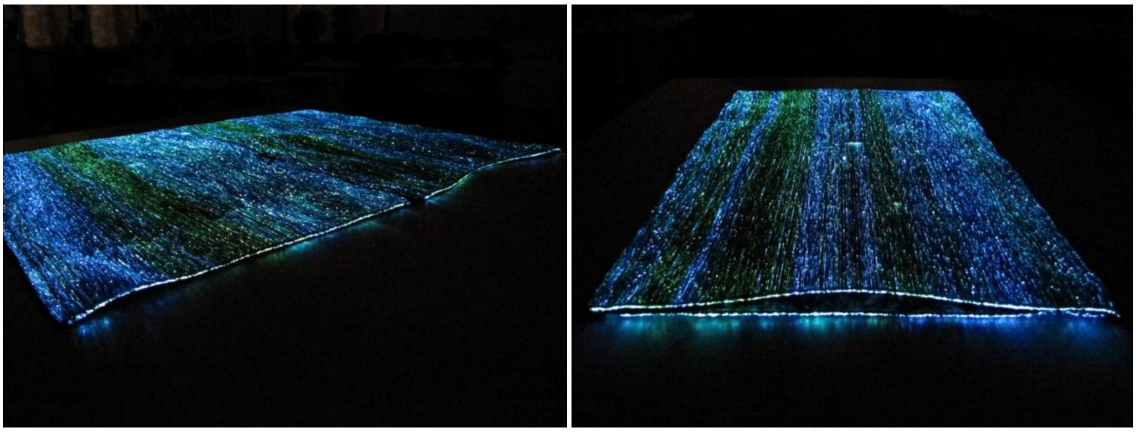


Figure 7.27 The enhanced luminescent effect of the fibre-optic fabric by applying the final PCB prototype

7.2 System Presentation

A collection of a lady's and a man's SMART clothing consisting of an undercoat and an overcoat is further described and discussed.

7.2.1 Energy harvesting jacket/coat

<u>Womenswear</u>

The design and making up process from a toile garment to a ready-made garment for the requirements of the lady’s jacket are presented in Figures 7.28 and 7.29, with the careful and precise incorporation and connection of the solar panels, circuitry and other electronic devices.

Figure 7.28 Lady's solar jacket sample – Front, side and back

Figure 7.29 Lady's ready-made solar jacket and pouch – Front, side and back

<u>Menswear</u>

In the collection of smart outerwear clothing, a solar harvesting coat for a man was also designed and made up, as seen in Figures 7.30 and 7.31.

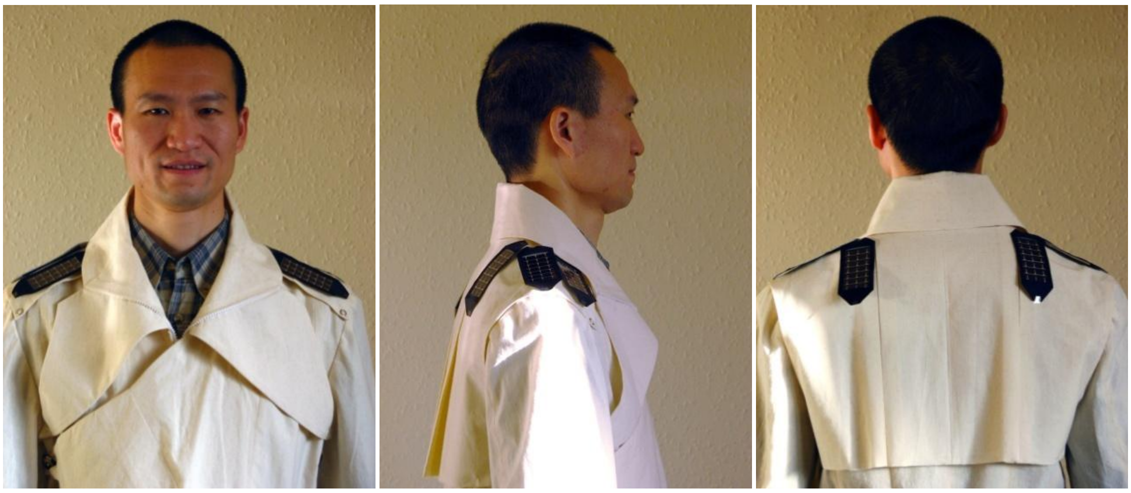


Figure 7.30 Man's solar coat sample – Front, side and back

Figure 7.31 Man's ready-made solar coat – Front, side and back

7.2.2 Mood changing vest

Womenswear

One-piece lady's mood changing vest was shaped by a draping method and carefully made by employing couture techniques, from toile designed sample to the made up garment, as shown in Figure 7.32. By integrating the sound control, LED lighting and colour changing, as well as by precisely connecting the PCB, the SMART garment has been realised. Figures 7.33 and 7.34 present the luminescent colour effects of this garment by sound changes.

Figure 7.32 Lady's luminescent vest – from sample to ready-made with front, side and back views

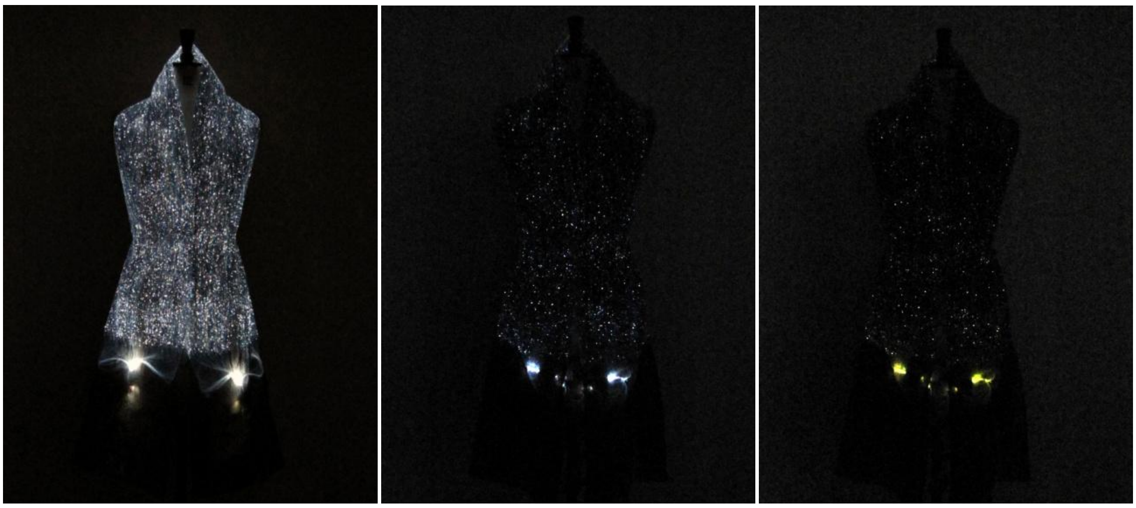


Figure 7.33 Presentation of the first PCB prototype with a faded visibility through the fibre-optic fabrics, comparing with the non sound-activated white LEDs

Figure 7.34 Presentation of the updated PCB prototype with single-coloured gradual luminance induced by increasing sound

<u>Menswear</u>

Figure 7.35 displays a mood changing vest for the man, shaped by two pieces of luminescent fabrics with side zipper closures and cotton linings. The final PCB was successfully integrated in the man's luminescent vest and presented in Figure 7.37. A comparison of the effect with a non sound-activated example is shown in Figure 7.36.

Figure 7.35 Man's luminescent vest – from sample to ready-made with front, side and back views

Figure 7. 36 Non sound-activated prototype with white LED lighting – Front, side and back

Figure 7.37 Presentation of the final PCB prototype with the man’s mood changing vest – Front, side and back

7.2.3 SMART suit

The established SMART suits with high aesthetics constitute the SMART clothing system, shown in Figure 7.38. Design and technology integration underpins the newly made collection of SMART clothing designs capable of energy harvesting and mood changing, fulfilling all aims of this research project. The CD included in this thesis shows a dynamic, real-life presentation of this work presented on two real human models.

Figure 7.38 Presentation of the collection of energy harvesting and SMART mood changing clothes – Front and back

CHAPTER 8 – DISCUSSION AND CONCLUSION

8.1 Discussion

This project has investigated, designed and developed a collection of fashionable SMART mood changing clothes which consist of fibre optic and photovoltaic technologies without any compromise of aesthetics. The tailor-made clothing prototypes consist of an outer garment and an inner garment suit for a lady and a man. These clothing systems have high levels of functionality and intelligence. Both undergarments change colour via voice stimulation by the mood of the wearer, self-powered and charged by the sun through the use of PV technology. PV panels can also charge mobile devices carried by the user, such as a mobile phone or an MP3. New properties like flexibility and miniaturization are infused in the clothing design aesthetics.

For achieving mood-dependant changes, auditory input was integrated in the clothing by a wearable computer, half the size of a credit card, which can sense the physiological changes in the mood of the wearer by detection of the pitch of his/her voice. By breaking the sound signals into different voltages, the corresponding colour commands are transmitted to the garments which are made of woven scattering fibre optics and activated by small light emitting diodes, used as an input light source.

Fibre optics and LEDs have previously been applied for illuminating applications on clothing. But their colour dynamic change according to the human's physiological and psychological state in real time has never been considered before and it is original. Therefore this project, for the first time, has developed a responsive illuminating fibre optic fabric system with colour changing output by responding to a sound stimulus via wearable electronic control integrated in the garment and hence developing an intimate communication between human and clothing.

With regard to the photovoltaic thin film technology, the power supply and its charging system have also been conceived and developed in this research for powering the wearable information system, which is also another original aspect. In consideration of the limited flexibility and inextensibility of the PV films, small but effective PV modules have been used in a creative but practical packaging design, by solving technological challenges on power and connectivity. The optimum location for the energy harvesting system has also been established, so that the positioning of the PV films is ideal and it is integrated and blended with the overall design of the clothing system.

The bulky and constrained wire-based connections seen in previous SMART clothing have been eliminated by using special conductive fabric interlining for better flexibility, optimal wearability and comfort. The clothing system has been further optimised by snap fasteners which are detachable giving more emphasis on the aesthetic and comfort appeal of the clothing. These gripper snaps are excellent connectors between fabrics and electronics, and have provided effective and robust electrical contacts. In this way modular components can be easily snapped into clothing and removed for washing or replaced when faulty. At the same time, insulation of all modular parts has also been carefully carried out prior to the assembly of the entire clothing for increasing working efficiency.

Having had the opportunity of working in a funded research project for *Monitoring a Soldier's Health [3]*, considerable advanced work has been incorporated into this project by applying various conductive textiles as transmission lines and sensing electrodes.

8.2 Conclusion

The synergy of two concepts; the harvesting of solar energy and the changing of mood have been designed, developed and implemented in two SMART clothing suits, one for a lady and another for a man. Their innovative fibre optic fabric and garment designs, with wearable electronic, computational and responsive information technologies have been realised by using textile based conductive strips of fabric and snap on/off fasteners where possible. Optimisation of the LEDs, the battery and their effective connection with the wearable PCB has been realised. Voice detection, processing and colour illumination of the LEDs as colour inputs to the fibre optic garment have been investigated, tested, developed and integrated successfully into the clothing systems. Thereupon, the new concept of SMART clothing ambience has been realised by research and implementation of design/technology aspects, transcends disciplinary boundaries. The clothing systems are practical and have shown their effectiveness in a number of show presentations as illustrated in Appendix C. A live CD is produced and attached to this thesis.

8.3 Future Work

The styling and tailoring of the clothes developed in this project could be developed further using smart woven and knitted fabrics, to supply free of cutting clothing. Finer diameter optical fibres and miniature LEDs would be necessary to produce further flexible, bendable even stretchable structures for clothing applications. The properties of the luminescence of the fibre optics and the lumen of the LEDs (especially the red colour) need to be increased whilst maintaining or reducing their dimensions.

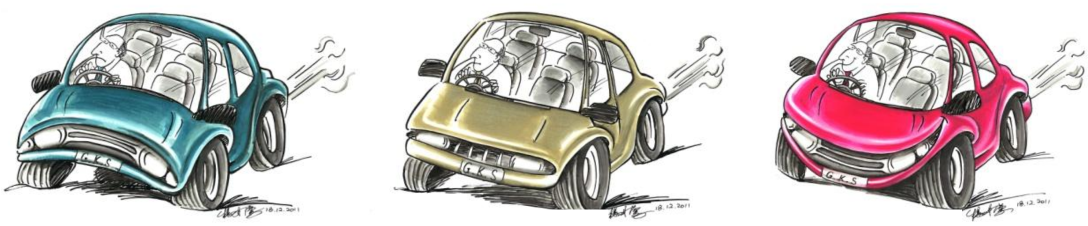
Due to insufficient and not so stable energy conversion, the current conversion efficiency is between 11-18% of the thin film solar cells used [86]. Research for improving the efficiency of solar energy harvesting by further investigating more advanced PV panels is one aspect worth investigating further. The supplementary design that connects the panels to the devices is just as important. Maximum Power Point Tracking (MPPT) is an advanced electronic system that optimizes the electrical operating point of the PV modules in a way to extract the highest possible power from the modules [96] [97]. The PV system can be effectively developed with this dynamic tracking method using updated microprocessors with appropriate MPT algorithms to get the maximum output power under any given environmental conditions [98] [99].

The most restricting materials used in the clothing system are the limited flexibility of the solar panels and the rigid substrate of the PCBs. The existing film-like PV panel can only bend in one direction rather than being fully flexible as a woven textile. New research of depositing photovoltaic devices directly onto textile substrates is challenging. A Flexible Circuit Board (FCB) can also substitute the rigid substrate of the current PCB to promote flexibility and lighter weight. The effective working of the whole system is another challenge because one has to overcome the stress concentration of the incompatible connections causing problems between the electronic components and the textile substrate. The rechargeable battery of a smaller size, even flexible can be considered and improved as technology develops rapidly.

It is worth noting that conductive textiles would be very effective if incorporated directly into the fabric structure of the clothing for data and power distribution as well as for sensing by the PCB circuitry being part of the fabric and hence comfortable and completely unnoticeable. In accordance to the tight-fitting and stretchable clothing design requirements, an elastic conducting fabric needs to be realised.

Aiming at improving the non-linear property of sound, its frequency programming design can be further investigated and improved. Expression of mood by detecting voice researched in this project is only one approach in determining physiological and psychological changes in humans. Other senses such as touch, taste and smell could also be developed, through some way be more challenging.

Finally a direct relationship of the effect of this system on the mood of the wearer can be realised by using a portable EEG and detecting directly the activity of the user's brain (Figure 8.1). Such technology has been researched by Professor Stylios and results may appear in the near future.



SAD *NORMAL* *HAPPY*

Figure 8.1 SMART mood changing technology

REFERENCE

[1] Shrobe, H.E., *Foreword*, in *Smart Environments: Technology, Protocols and Applications*, S.K.D. Diane J. Cook, Editor. 2005, Wiley-Interscience: New Jersey.

[2] Abate, A.F., et al., *MUBAI: multiagent biometrics for ambient intelligence.* Journal of Ambient Intelligence and Humanized Computing, 2010. **2**: p. 9.

[3] Stylios, G.K., *Private Communication.* 2012.

[4] Budd, M., *Aesthetics*, in *Routledge Encyclopodia of Philosophy*. 1998: London.

[5] Kant, I., *The Critique of Judgment*. 1790, Meredith, Oxford: Oxford University Press, 1928.

[6] Sibley, F., *"Aesthetic Concepts," Philosophical Review*. Approach to Aeshtetics. Vol. 68. 1959: Clarendon: Oxford, 2001. 421-450.

[7] *Art*. Britannica Online Encyclopedia [cited 2011 20-07]; Available from: http://www.britannica.com/EBchecked/topic/630806/art.

[8] Gethmann-Siefert, A., *Introduction to Aesthetics*. 1995, Munich: Wilhelm Fink.

[9] Pham, B., *Design for aesthetics: interactions of design variables and aesthetic properties.* Proceeding of SPIE IS&T/SPIE 11th Annual Symposium - Electronic Imaging '99, San Jose USA, 1999. **3644**: p. 364-371.

[10] Lee, S., *Fashioning the Future: Tomorrow's Wardrobe*. 2005, Thames & Hudson: London. p. 15-18.

[11] Lukowicz, P., et al., *WearNET: A Distributed Multi-sensor System for Context Aware Wearables* Computer Science, 2002. **2498/2002**: p. 361-370.

[12] Crabb, G., *Technology*, in *Universal Technological Dictionary, or Familiar Explanation of the Terms Used in All Arts and Sciences, Containing Definitions Drawn From the Original Writers*. 1823, London: Baldwin, Cradock and Joy.

[13] Bain, R., *Technology and State Government.* American Sociological Review, 1937. **2**(NO. 6): p. 860-874.

[14] *Science*. Merriam-Webster [cited 2011 15-08]; Available from: http://www.merriam-webster.com/dictionary/science.

[15] Dugger, W.E., *The Relationship between Technology, Science, Engineering, and Mathematics*, in *The Annual Conference of the American Vocational Association*. 1993. p. 4-8.

[16] Smith, R.J. *Engineers' Council for Professional Development definition on Encyclopaedia Britannica* [cited 2011 10-09]; Available from: http://www.britannica.com/EBchecked/topic/187549/engineering.

[17] Tang, S.L.P. and G.K. Stylios, *An Overview of Smart Technologies For Clothing Design and Engineering* International Journal of Clothing Science and Technology, 2006. **18**(No. 2): p. 108-128.

[18] Heilbron, J.L., ed. *The Oxford Companion to the History of Modern Science* 2003, Oxford University Press: New York. vii.

[19] Lee, S., *You Wear What You Eat*, in *Future Materials*. 2006, World Textile Publication Ltd. p. 19.

[20] Quinn, B., *Fashion and the Built Environment*, in *Techno Fashion*. 2002, Berg Publishers: Oxford. p. 11-13.

[21] Bolton, A., *Functionality*, in *The Supermodern Wardrobe*. 2002, V&A Publications: London. p. 15-19.

[22] Kirstein, T., et al., *Context aware textiles for wearable health assistants*, in *Intelligent textiles and clothing*, H. Mattila, Editor. 2006, Woodhead Publishing Limited and CRC Press LLC: Cambridge, England. p. 402-403.

[23] Nakad, Z.S., *Architectures for e-Textiles*, in *Computer Engineering*. 2003, Virginia Polytechnic Institute and State University: Blacksburg, Virginia.

[24] *mp3blue*. [cited 2011 16-08]; Available from: http://www.mp3blue.de/frameset.htm.

[25] *Solar Sev - Solar Panels*. 2004 [cited 2007 02-02]; Available from: http://www.scottevest.com/v3_store/access_solar.shtml.

[26] *Ermenegildo Zegna solar-powered jacket*. [cited 2007 15-10]; Available from: http://www.techdigest.tv/2007/10/ermenegildo_zeg.html.

[27] *Puddlejumper luminescent raincoat*. [cited 2008 08-05]; Available from: http://www.mintymonkey.com/puddlejumper_p1.html.

[28] *Lumalive photonic textiles*. [cited 2008 23-04]; Available from: http://www.lumalive.com.

[29] *Luminex*. 2006 [cited 2008 14-05]; Available from: http://www.crunchwear.com/category/companies/luminex.

[30] Tao, X., *Smart technology for textiles and clothing*, in *Smart Fibres, Fabrics and Clothing*, X. Tao, Editor. 2001, Woodhead Publishing Ltd. and CRC Press LLC. p. 1-6.

[31] Solon, O. *Brainwave-controlled cat ears for humans created by Japanese Neurowear*. 2011; Available from: http://www.wired.co.uk/news/archive/2011-05/5/neurowear-cat-ears.

[32] Bosshard, P., *An Assessment of Solar Energy Conversion Technologies and Research Opportunities*. Summer 2006, Stanford University.

[33] Harb, A., *Energy harvesting: State-of-the-art.* Renewable Energy, 2010. **36**(10): p. 2641-2654.

[34] Addington, D.M. and D.L. Schodek, *Smart components, assemblies and systems*, in *Smart Materials and Technologies: for the architecture and design professions*. 2005, Architectural Press: London. p. 180-185.

[35] *Cells, Modules, & Arrays*. [cited 2011 07-09]; Available from: http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/index.htm.

[36] Messenger, R. and J. Ventre, *Present and proposed PV cell*, in *Photovoltaic systems engineering*. 2000, CRC Press.

[37] Wenham, S.R., et al., *Semiconductors and P-N Junctions*, in *Applied Photovoltaic*. 2007, Earthscan: London.

[38] *Flexible Solar Panels 3v-4v*. [cited 2006 29-11]; Available from: http://www.siliconsolar.com/shop/catalog/Flexible-Solar-Panels-3v-4v-05-1284-p...

[39] Winter, M. and R.J. Brodd, *What Are Batteries, Fuel Cells, and Supercapacitors?* Chemical Review, 2004. **104**: p. 4245-4269.

[40] *How A PV System Works*. [cited 2011 07-09]; Available from: http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/index.htm.

[41] *Charge Controllers for Stand-Alone Systems*. A Consumer's Guide to Energy Efficiency and Renewable Energy [cited 2011 14-09]; Available from: http://www.energysavers.gov/your_home/electricity/index.cfm/mytopic=10640.

[42] Brown, D. *Battery Charging Options for Portable Products*. Analogic Tech, TA-100 2006 [cited 2011 13-09]; Available from: www.analogictech.com/designsupport/techarticles.php.

[43] Wylie, A. *The first monolithic integrated circuits*. 2009 [cited 2011 14-09]; Available from: http://homepages.nildram.co.uk/~wylie/ICs/monolith.htm.

[44] *SOFTswitch*. [cited 2011 14-08]; Available from: http://www.softswitch.co.uk.

[45] Cho, G., S. Lee, and J. Cho, *Review and Reappraisal of Smart Clothing*, in *Smart Clothing Technology and Applications*, G. Cho, Editor. 2010, CRC Press: New York.

[46] Hawken, P., A. Lovins, and H. Lovins, *Natural Capitalism: Creating the Next Industrial Revolution*. 1999: Little, Brown & Company.

[47] *Energy saving light bulbs take over*. [cited 2011 21-09]; Available from: http://www.energysavingtrust.org.uk/Resources/Features/Features-archive/Energy-saving-light-bulbs-take-over.

[48] Tao, X., ed. *Wearable photonics based on integrative polymeric photonic fibres*. Wearable electronics and photonics, ed. X. Tao. 2005, Woodhead Publishing Ltd and CRC Press LLC: Cambridge. p. 145-152.

[49] Hart, J.A., S.A. Lenway, and T. Murtha (1999) *A History of Electroluminescent Displays*.

[50] King, C.N. *Electroluminescent Displays*. in *MRS (Materials Research Society) Proceedings*. 1998: Cambridge University Press.

[51] *Nick Holonyak, Jr. 2004 Lemelson-MIT Prize Winner*. [cited 2011 21-07]; Available from: http://web.mit.edu/invent/a-winners/a-holonyak.html.

[52] Thyagarajan, K. and A.K. Ghatak, *Fiber Optic Essentials*. 2007, New Jersey: John Wiley & Sons, Inc.

[53] Addington, M. and D. Schodek, *Smart components, assemblies and systems*, in *Smart Materials and Technologies: for the architecture and design professions*. 2005, Architectural Press: London. p. 173-180.

[54] *Fiber Optics: Theory and Applications*. Technical Memorandum 100 [cited 2011 27-09]; Available from: http://www.photonis.com/en/content/26-ism-learning-center-library.

[55] *Luminex: Light emitting fabrics*. Techpak [cited 2008 14-05]; Available from: http://www.yet2.com/app/list/techpak?id=36635&sid=90&abc=0...

[56] *Star Cloth*. Starscape Fibre Optic & LED Lighting [cited 2012 03-02]; Available from: http://www.starscape.co.uk/star_cloth_technical.html.

[57] *Luminescent Fabric*. Luminex™ [cited 2009 05-11]; Available from: http://www.luminex.it/index.html.

[58] Thayer, R.E., *The Origin of Everyday Moods: Manging Energy, Tension, and Stress*. 1996: Oxford University Press, Inc.

[59] Thayer, R.E., *Toward an Understanding of Nonpathological Mood States: Evidence, Speculations, and Applications*, in *The Biopsychology of Mood and Arousal*. 1989, Oxford University Press, Inc.: New York. p. 147-152.

[60] Kasschau, R.A., *Sensation and Perception*, in *Psychology: Exploring Behavior*. 1985, Prentice-Hall. p. 186-187.

[61] Goldstein, E.B., *Sensation and Perception*. 2010, Belmont, USA: Wadsworth, Cengage Learning.

[62] Maxwell, J.C., *On the Theory of Compound Colours, and the Relations of the Colours of the Spectrum.* Philosophical Transactions of the Royal Society of London 1860. **Vol. 150**: p. 57-84.

[63] Gregory, R.L. and A.M. Colman, *Sensation and Perception*. Longman Essential Psychology Series. 1995, London and New York: Longman Pub Group

[64] *Sound pressure and Sound power - Effect and Cause* UdK Berlin Sengpiel 2009 [cited 2011 25-07]; Available from: http://www.sengpielaudio.com/SoundPressureAndSoundPower.pdf.

[65] Kirkeby, I.M., *Transferable knowledge.* Architectural Research Quarterly, 2011. **Vol. 15**(No.1): p. 9-14.

[66] Augé, M., *Non-places: introduction to an anthropology of supermodernity*. 1995, London, New York: Verso.

[67] Quinn, B., *Introduction*, in *Techno Fashion*. 2002, Berg: Oxford, New York. p. 6.

[68] Shaeffer, C.B., *Couture Sewing Techniques*. 1993: The Taunton Press.

[69] Philipson, N.W., *Creative Design for Fashion and Embroidery*. 1976, London: Cassell & Collier Macmillan Publishers Ltd. p.71-78.

[70] Hodge, B., *Skin + Bones: Parallel Practices in Fashion and Architecture*. 2006, New York: Thames & Hudson Inc.

[71] *Digital Dawn*. Loop.pH 2004 [cited 2009 07-05]; Available from: http://www.loop.ph/bin/view/Loop/DigitalDawn.

[72] Jing, M., *House with abundant rays of hope*, in *China Daily*. 2010.

[73] *'Time and Space'*. A zero emission house 2010 [cited 2012 07-02]; Available from: http://www.texpopark.com/Article/ShowArticle.asp?ArticleID=118.

[74] *The death of ineffective conferences and presentations?* amBX UK LTD [cited 2011 21-09]; Available from: http://www.ambx.com/.

[75] *Decoration Collection*. LumiGram [cited 2008 21-08]; Available from: http://www.lumigram.com/catalog/index.php.

[76] Emerson, S., *Design: A Creative Approach*. International Textbooks in Art Education, ed. I.L.D. Francesco. 1953, Scranton: International Textbook Company.

[77] Sullivan, L., *The Tall Office Building Artistically Considered*, in *Lippincott's Magazine*. March 1896.

[78] Cillo, P. and G. Verona, *Search Styles in Style Searching: Exploring Innovation Strategies in Fashion Firms.* Long Range Planning, 2008. **Vol 41**: p. 650-671.

[79] Cappetta, R., P. Cillo, and A. Ponti, *Convergent designs in fine fashion: An evolutionary model for stylistic innovation.* Research Policy, 2006. **35**: p. 1273-1290.

[80] Barthes, R., *The Fashion System*. 1983, New York: Hill and Wang.

[81] Mckelvey, K. and J. Munslow, *Fashion Design: Process, Innovation & Practice*. 2003, Oxford: Blackwell Science Ltd.

[82] Anderson, D.K. *Patternmaking: Past to Present*. 2005 [cited 2011 17-11]; Available from: www.techexchange.com.

[83] MacDonald, N.M. and R.E. Weibel, *Principles of Flat Pattern Design*. 1988, New Jersey: Prentice Hall, Englewood Cliffs.

[84] *Form Study Prototype (Model)*. Cool Prototyping [cited 2011 04-08]; Available from: http://www.coolprototyping.com/rapid-prototyping-glossary.asp.

[85] Bäumer, D., et al., *User Interface Prototyping – Concepts, Tools, and Experience*, in *the 18th International Conference on Software Engineering (ICSE)*. 1996: Berlin.

[86] Schubert, M.B. and J.H. Werner, *Flexible Solar Cells for Clothing.* Materialstoday, 2006. **9**(6).

[87] Dunne, L.E., S.P. Ashdown, and B. Smyth, *Expanding Garment Functionality through Embedded Electronic Technology*. Journal of Textile and Apparel, Technology and Management (JTATM), 2005. **4**(3).

[88] Redström, J., *Towards user design? On the shift from object to user as the subject of design.* Design Studies, 2006. **27**(2): p. 123-139.

[89] McCann, J., R. Hurford, and A. Martin. *A Design Process for the Development of Innovative Smart Clothing that Addresses End-User Needs from Technical, Functional, Aesthetic and Cultural View Points*. in *the 2005 Ninth IEEE*

International Symposium on Wearable Computers (ISWC'05). 2005: IEEE Computer Society.

[90] Vikram, J.G., *Ambient Electrnics*, in *Electronics For You*. February 2011, 2011 EFY Enterprises Pvt Ltd.: India. p. 40.

[91] McCreight, T., *Hot and Cold Connections for Jewellers*. 2007: BLOOMSBURY ACAD & PR.

[92] *Electrotextile Samples Pack*. Teaching Resources Ltd. [cited 2010 14-07]; Available from: www.mutr.co.uk.

[93] Soroka, W., *Fundamentals of packaging technology*. 1999: Institute of Packaging Professionals.

[94] Baldwin, C.Y. and K.B. Clark, *Design Rules, Volume 1: The Power of Modularity*. 2000: The MIT Press.

[95] Bolton, A., *Modular Systems*, in *The Supermodern Wardrobe*. 2002, V&A Publications: London. p. 28.

[96] Cullen, R.A. *What is Maximum Power Point Tracking (MPPT) and How Does it work?* Blue Sky Energy, Inc. [cited 2012 29-02]; Available from: www.blueskyenergyinc.com/uploads/pdf/BSE_What_is_MPPT.pdf.

[97] Musser, G. (2009) *Invert your thinking: Squeezing more power out of your solar panels*. Scientific American.

[98] Hussein, K.H., et al. *Maximum photovoltaic power tracking : an algorithm for rapidly changing atmospheric conditions*. in *Generation, Transmission and Distribution, IEE Proceedings-*. 1995: IET.

[99] Tung, Y.-J.M., A.P. Hu, and N.-K. Nair, *Evaluation of Micro Controller Based Maximum Power Point Tracking Methods Using dSPACE Platform*, in *Australian University power Engineering Conference*. 2006.

APPENDIX A – SPECIFICATIONS OF PCB DESIGN FOR THE SMART CLOTHING SYSTEM

Electronic components layout and circuit diagram of the final PCB made and applied in the SMART clothing system are shown in Figures A.1 and A.2, with the corresponding electronic components listed in Table A.1.

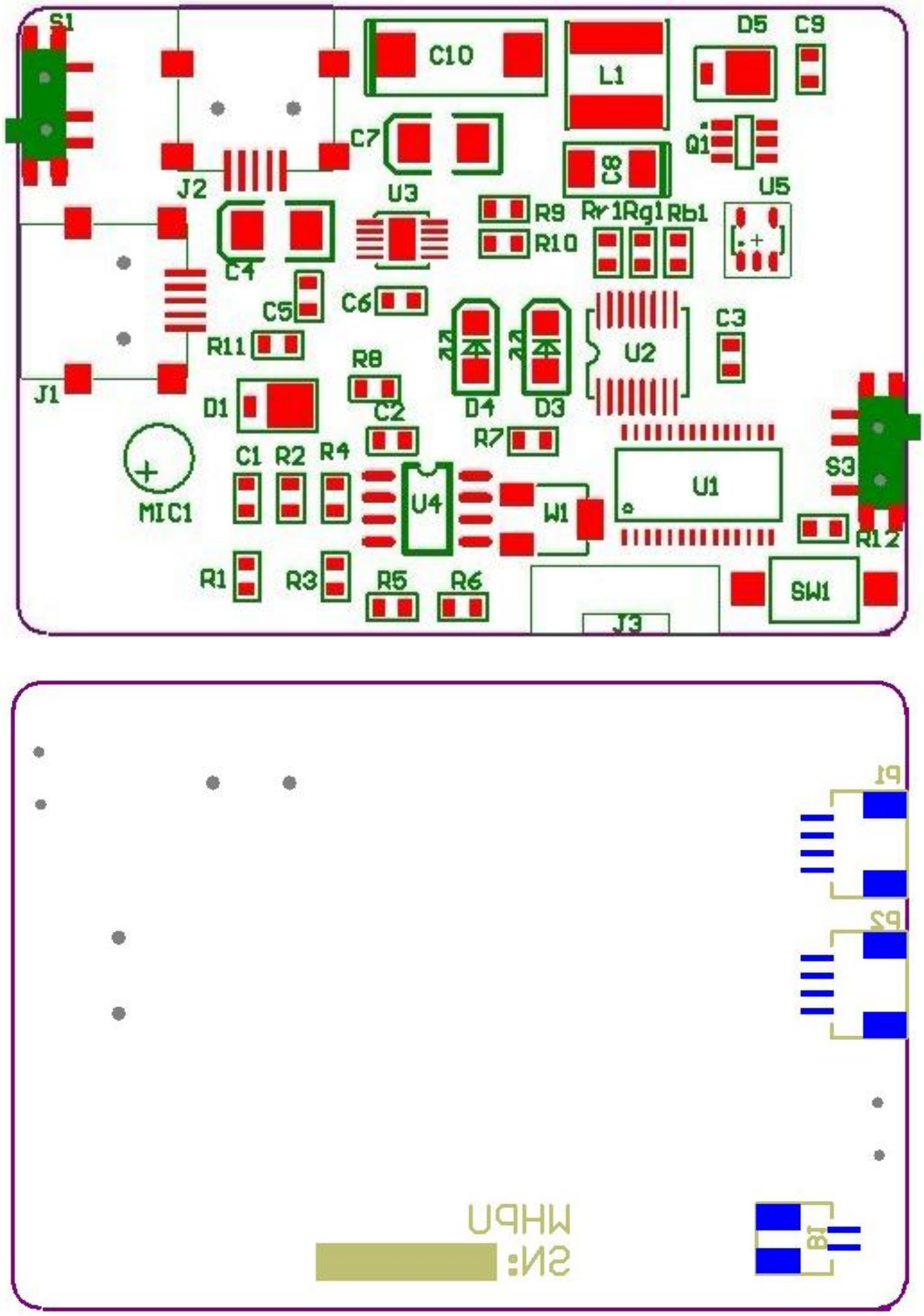


Figure A.1 Electronic components layout of the final PCB prototype – Front and back

Designator	Component	Part Type	Package
R1	Resistor	1K	603
R2	Resistor	32K	603
R3	Resistor	1K	603
R4	Resistor	130K	603
R5	Resistor	500	603
R6	Resistor	1K	603
R7	Resistor	360	603
R8	Resistor	360	603
R10	Resistor	1M6	603
R11	Resistor	360	603
R12	Resistor	10K	603
Rr1	Resistor	20	603
Rg1	Resistor	20	603
Rb1	Resistor	20	603
W1	Variable Resistor	5K	POT
C1	Capacitor	104	603
C2	Capacitor	104	603
C3	Capacitor	104	603
C4	Capacitor	4.7uF	C1210E
C5	Capacitor	22nF	603
C6	Capacitor	104	603
C7	Capacitor	4.7uF	C1210E
D1	Diode	SS14	D1810
D3	Indicator Diode	LED_R	LED
D4	Indicator Diode	LED_G	LED
D5	Diode	SS14	D1810
U1	MCU – Microchip Unit	LPC938	TSSOP28
U2	3-Channel Constant Current LED Driver	DM413	SOP16
U3	Integrated Li-Ion Charger IC	NCP1835B	DFN-10
U4	Audio Operational Amplifier	PM12135S	SO-8
U5	PWM Step-up DC-DC Controller	NCP1450A	TSO-5

S1	On-off Switch	SW SPDT	MSK-12C01
S3	On-off Switch	SW SPDT	MSK-12C01
SW1	Multi-control Switch	SW SPDT	MSK-12C01
J1	Charging Interface	USB in	MINIUSB-B
J2	Charging Interface	USB out	MINIUSB-B
J3	Programming Port	4 HEADER	IDC 8
P1	Connector	LED1_Connector	4 PIN
P2	Connector	LED2_Connector	4PIN
B1	Connector	Battery Connector	2PIN
Q1	Power Mosfet	NTG3446	TSOP-6

Table A.1 Electronic components information

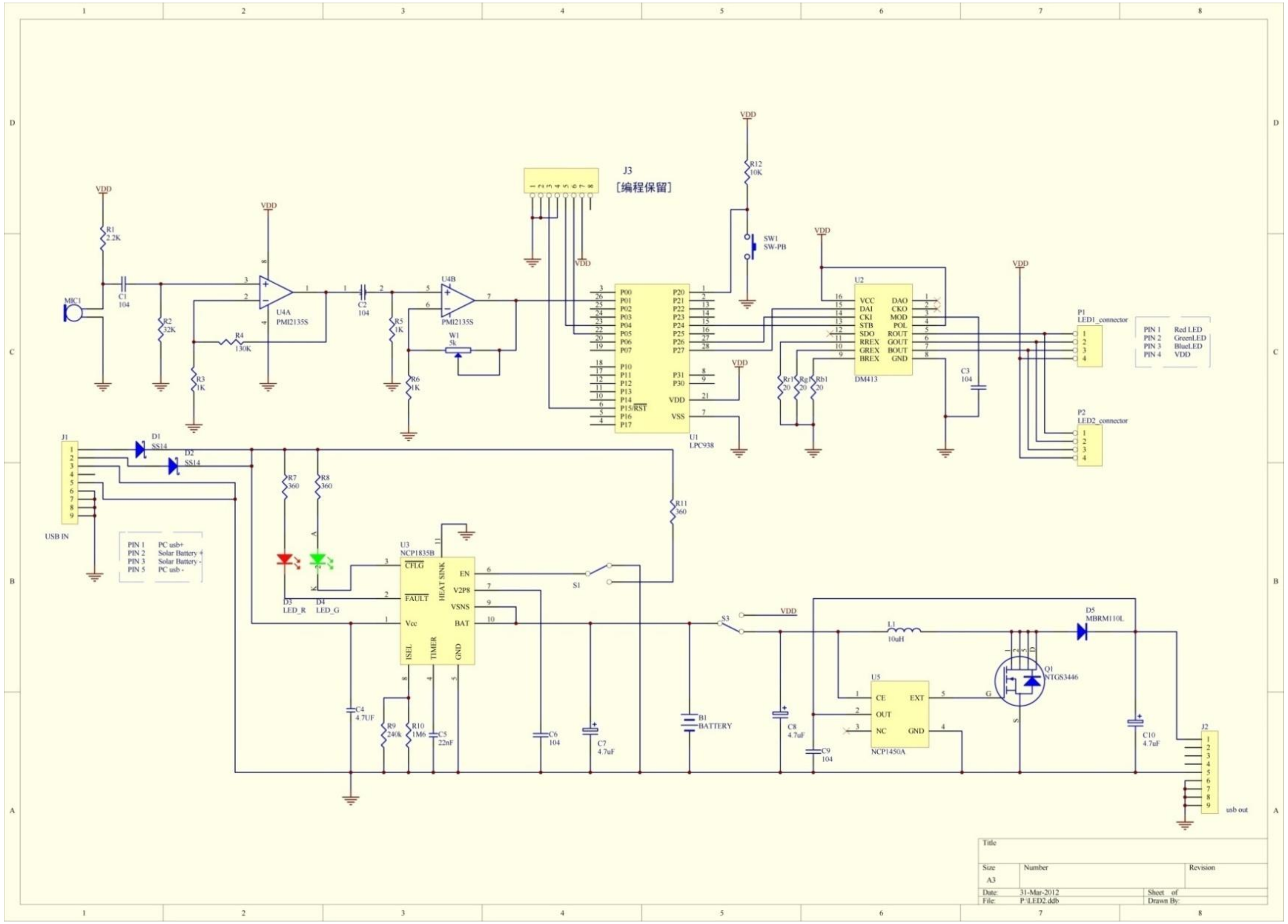


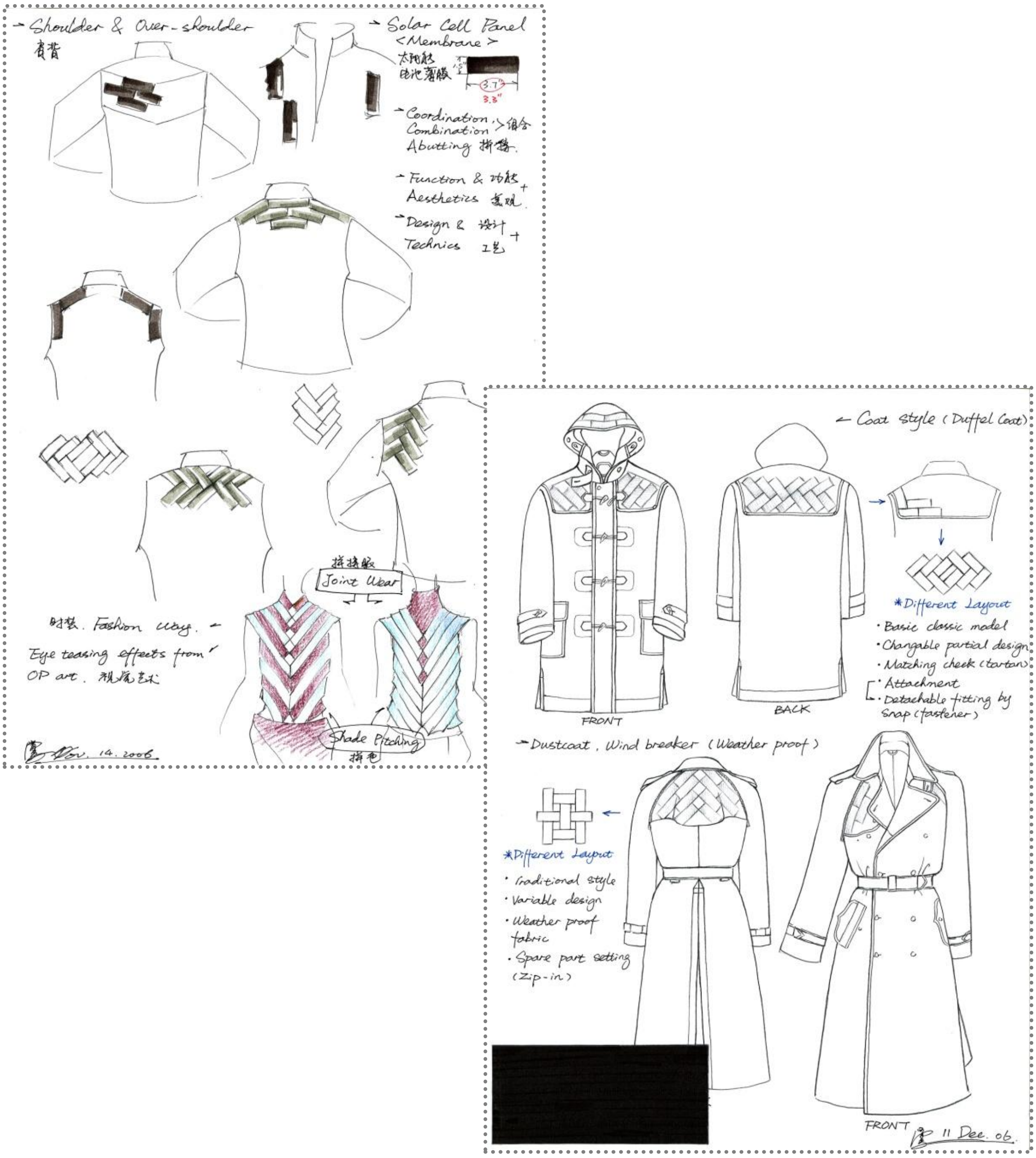
Figure A.2 Circuit diagram of the SMART clothing system – Energy harvesting and mood Changing

APPENDIX B – PRELIMINARY CLOTHING DESIGN DEVELOPMENT

This appendix shows all sketches of the preliminary clothing designs of this project, from the initial idea to the final collections. By considering PV films and fibre optic fabrics, different styles with details have been created from outerwear to innerwear.

B.1 Initial Ideas for the Photovoltaic Outerwear Garment Design

Exploratory investigation and designs for positioning solar panels on the exposed parts of the coats and jackets were illustrated in Figure B.1 with various pattern layouts.



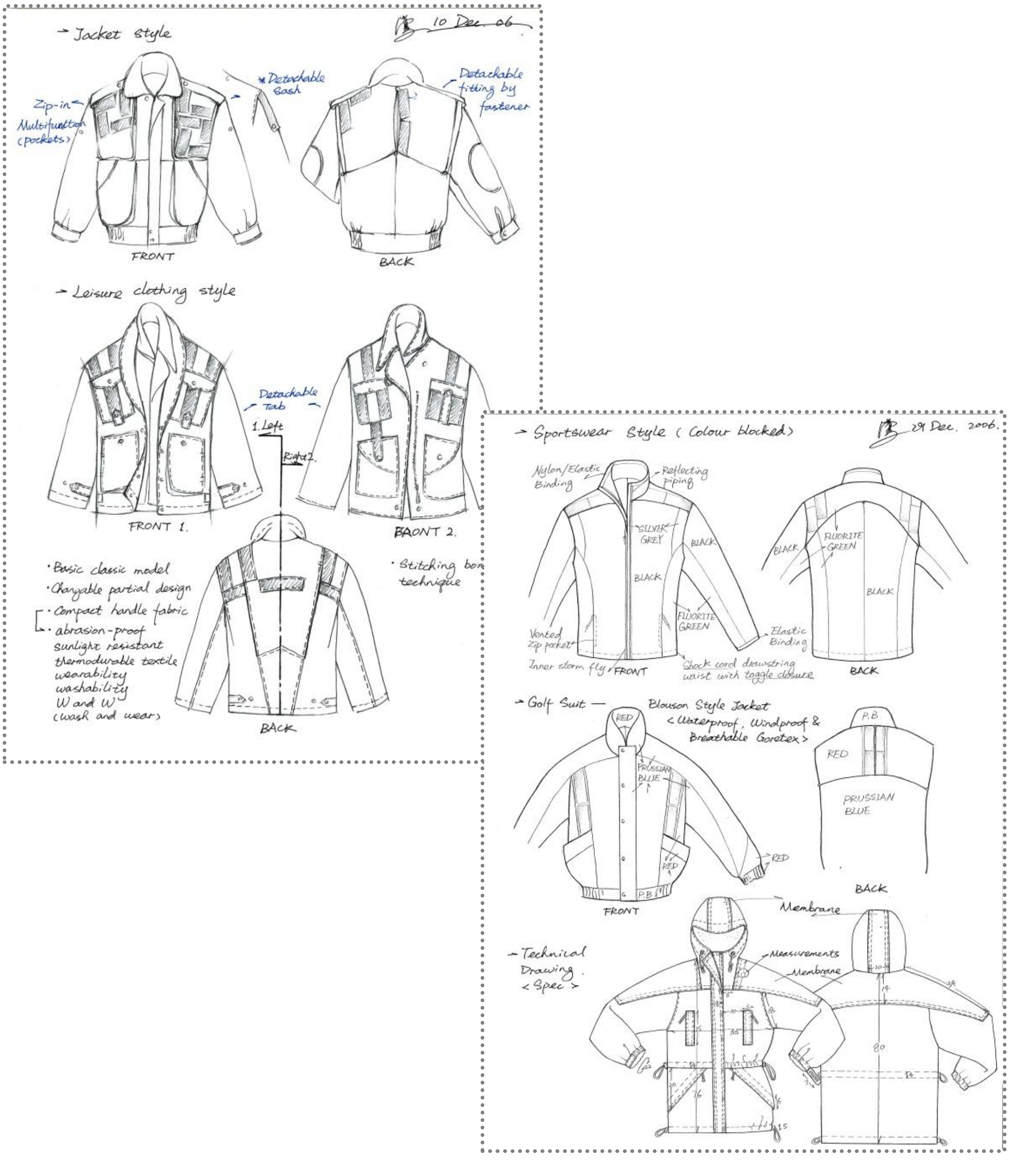


Figure B.1 Designing and positioning PV panels on coats and jackets as pattern layouts

Based on ideas of positioning the solar panels on the garment, a simple fashionable design range and collection have been conceived as shown in Figure B.2 for womenswear and Figure B.3 for menswear.

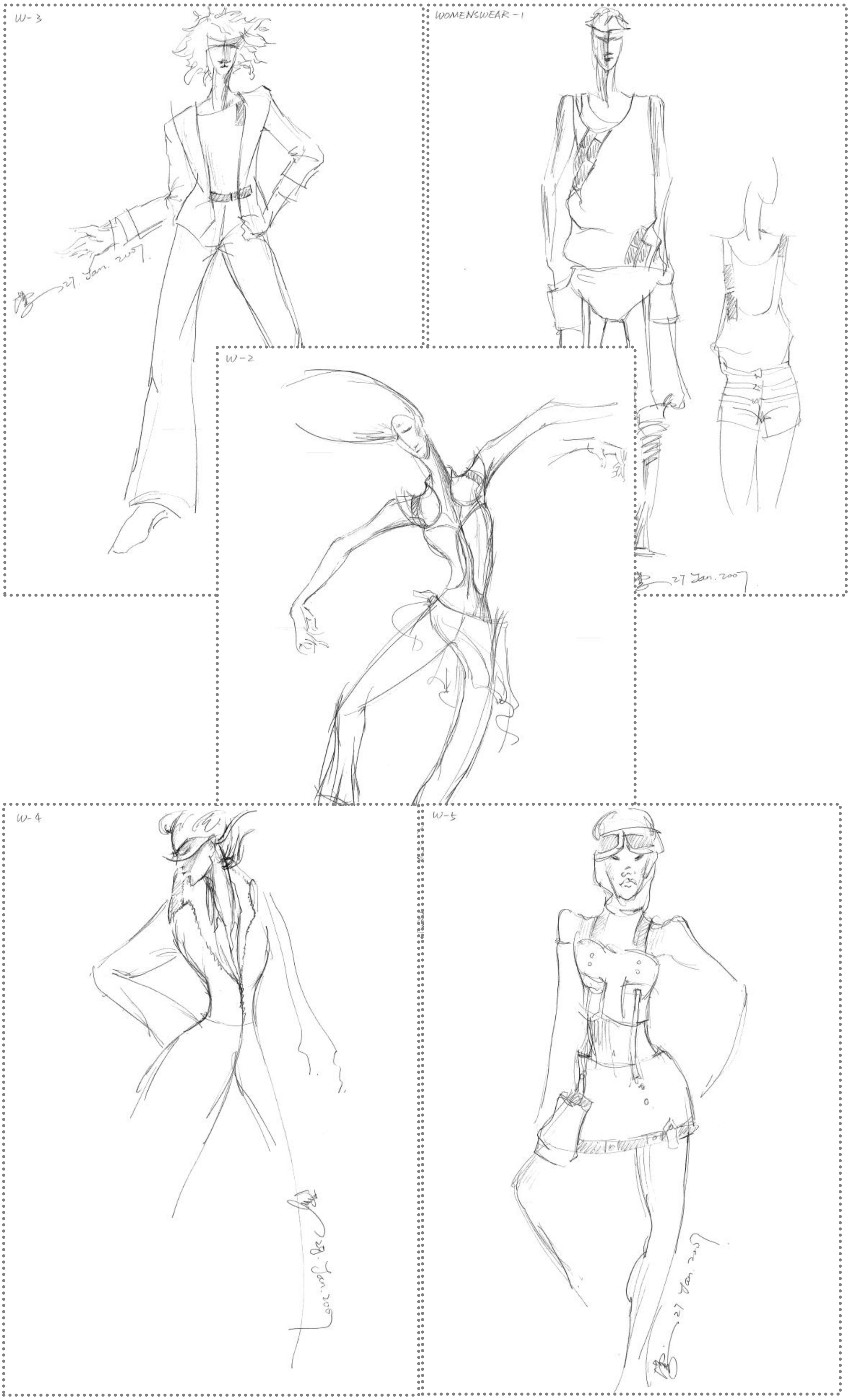


Figure B.2 Photovoltaic clothing for the initial womenswear collection

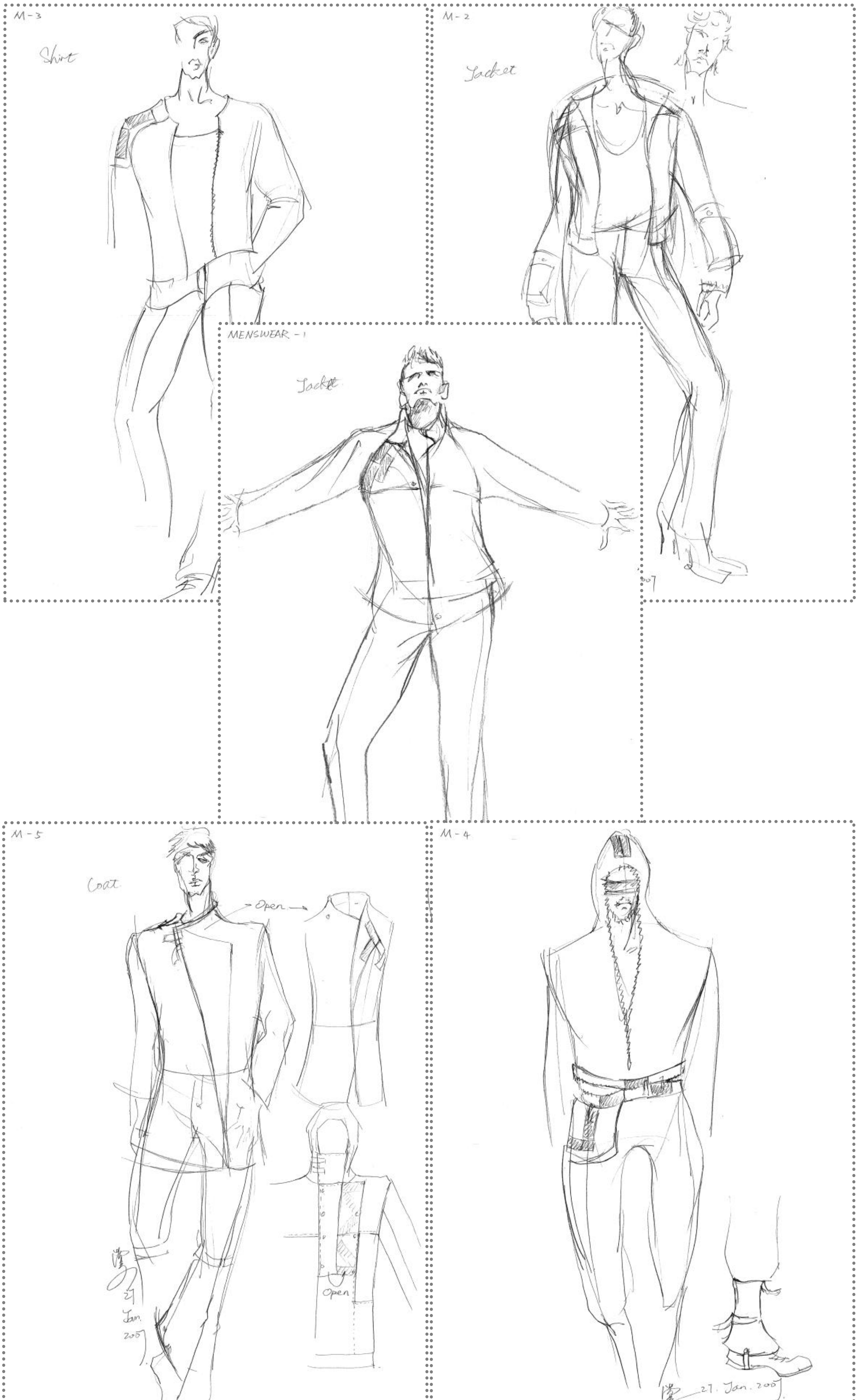
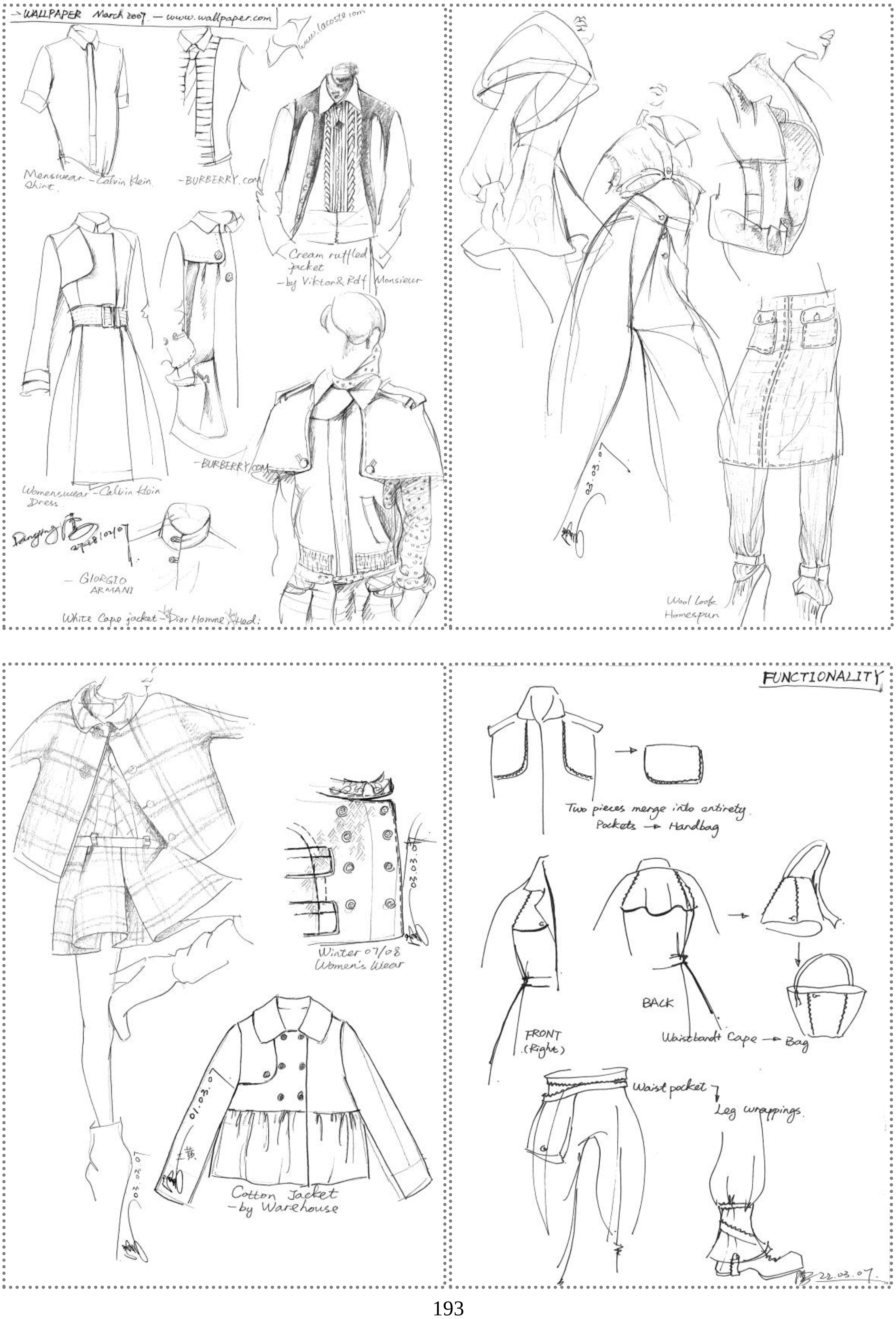


Figure B.3 Photovoltaic clothing for initial menswear collection

B.2 Outerwear Design Development

In line with Chapter 4, a series of sketches have been produced for the outerwear design. Details of collars, cuffs, fastenings and pockets are investigated and developed with the inspiration of clothing and origami, fashion and architecture, as shown in Figure B.4.




09.05.2007

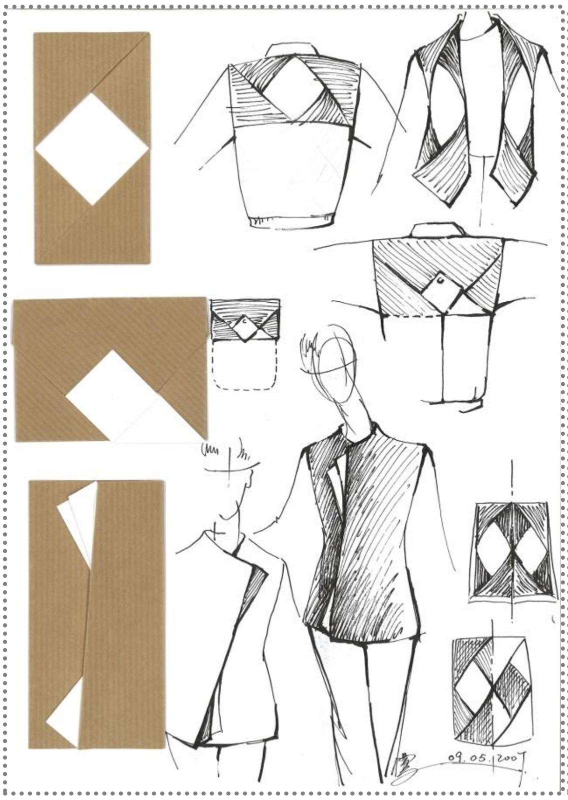
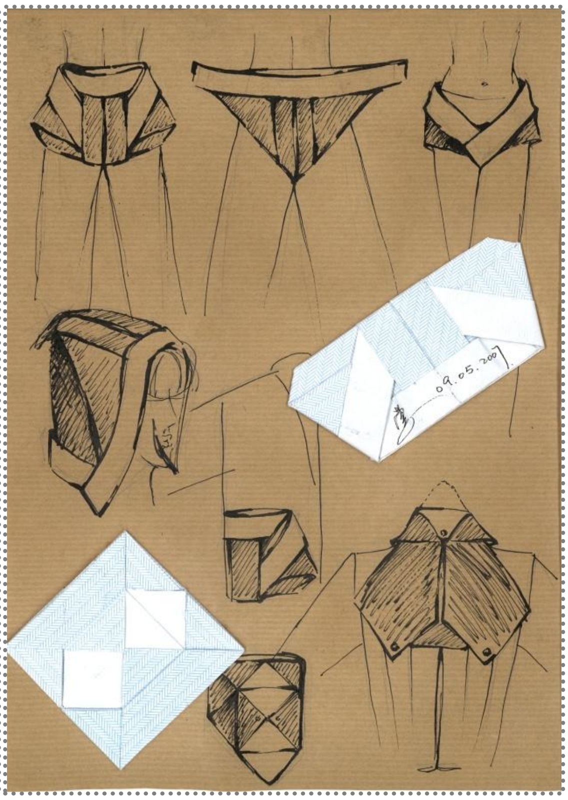
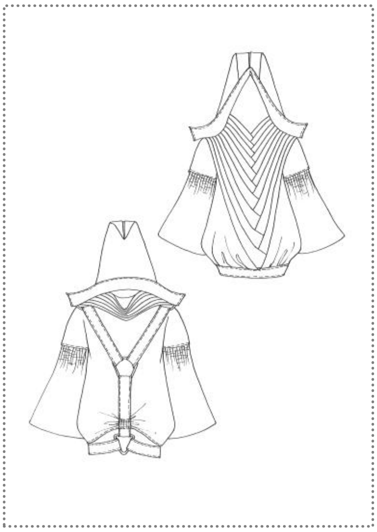
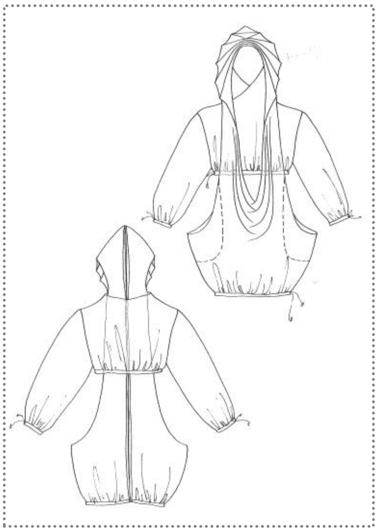
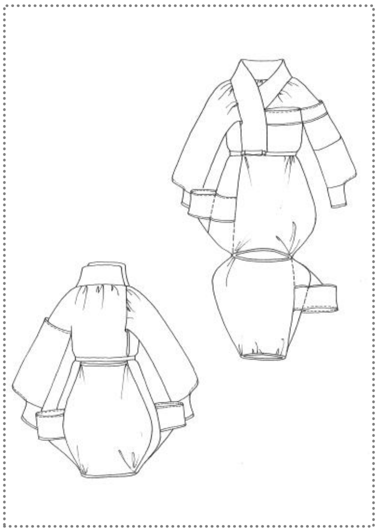
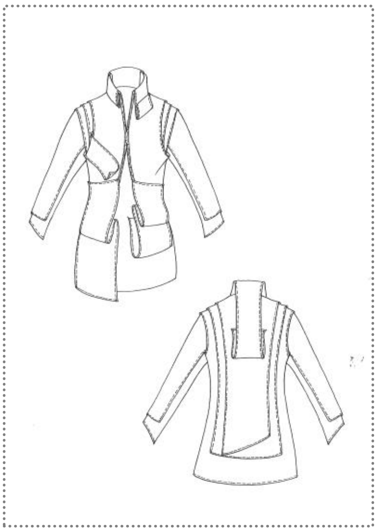
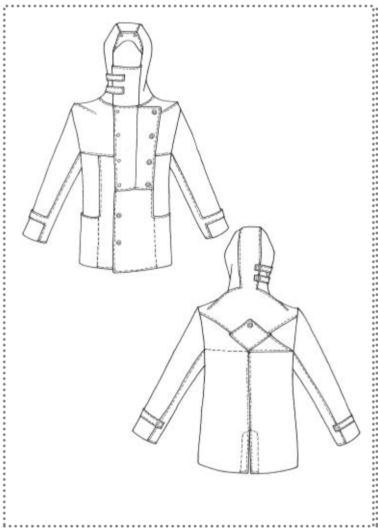
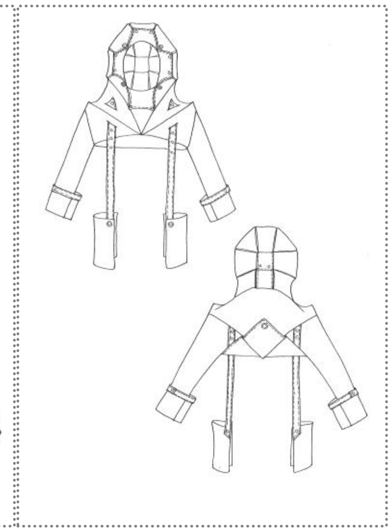
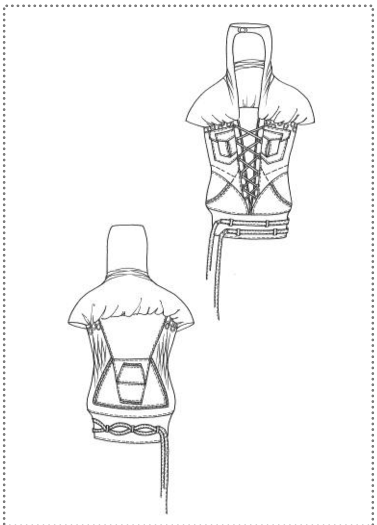
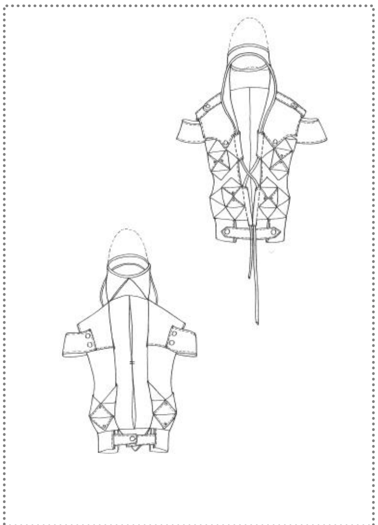
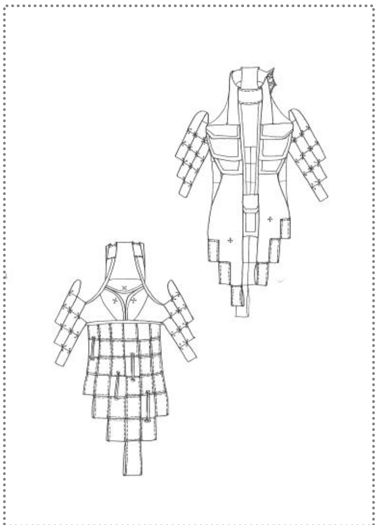
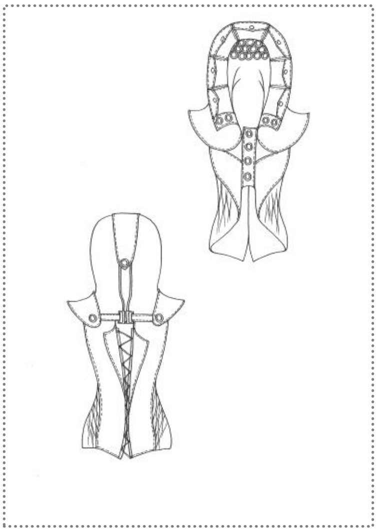
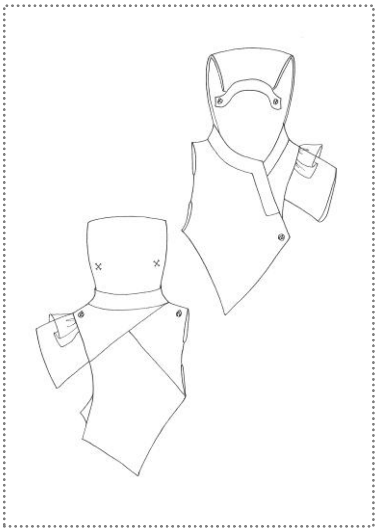
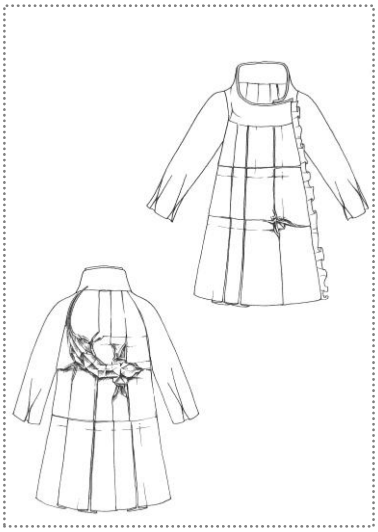
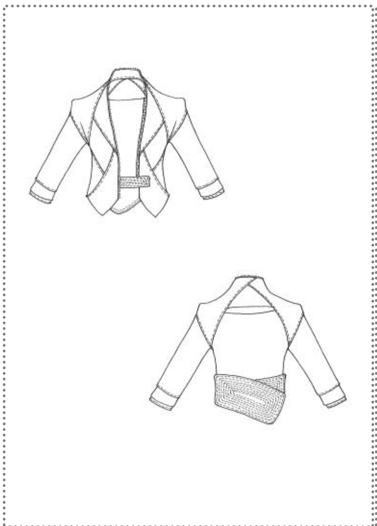
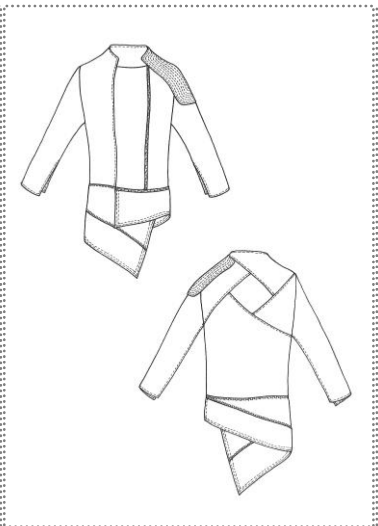
10.05.2007
14.05.2007

09.05.2007

09.05.2007

Figure B.4 A series of sketches to develop the outerwear design ideas from research inspiration

From this investigation, 36 original ideas of jackets/coats and 23 original ideas of trousers/dresses have been created for womenswear and menswear, as shown in Figures

B.5 and B.6, paying particular attention to the following areas; silhouette, proportion, balance and attention to details.

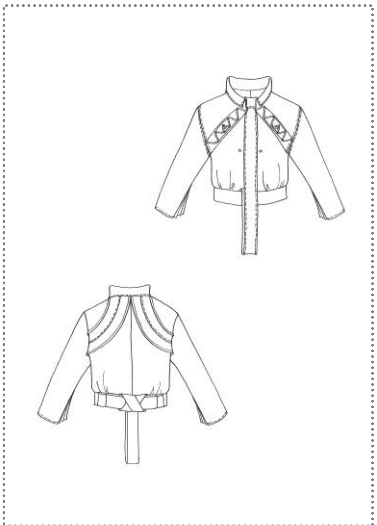
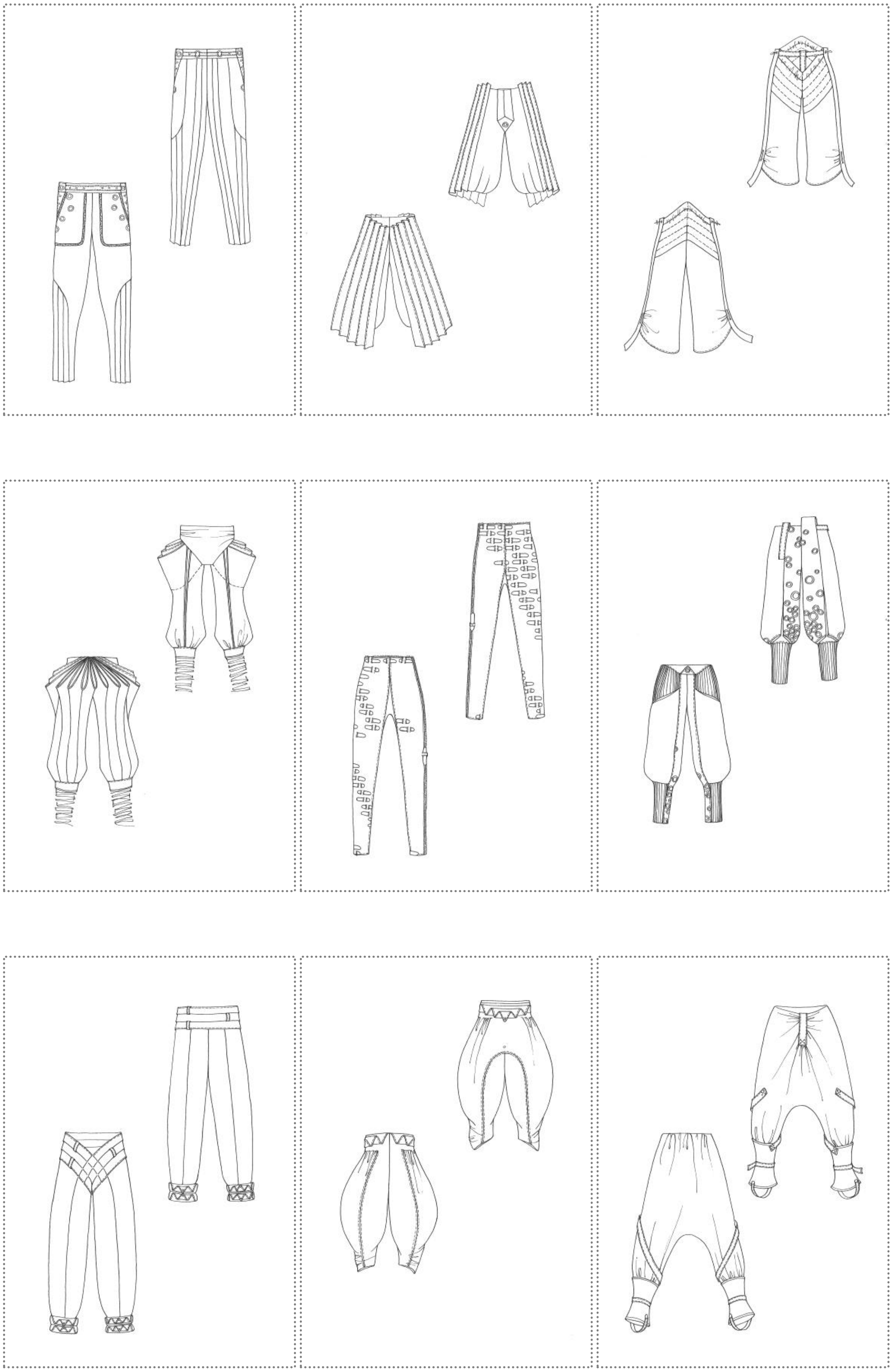


Figure B.5 36 original ideas of jackets/coats in the form of working drawings



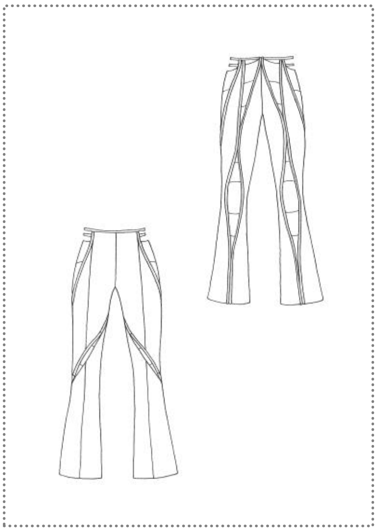
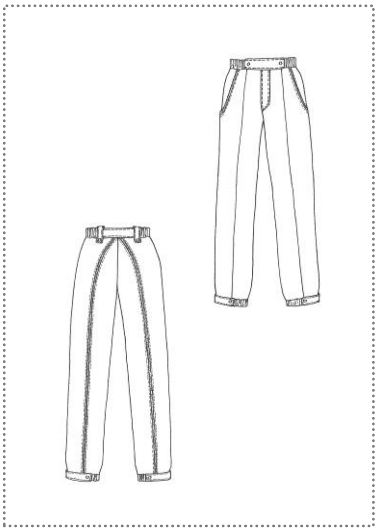
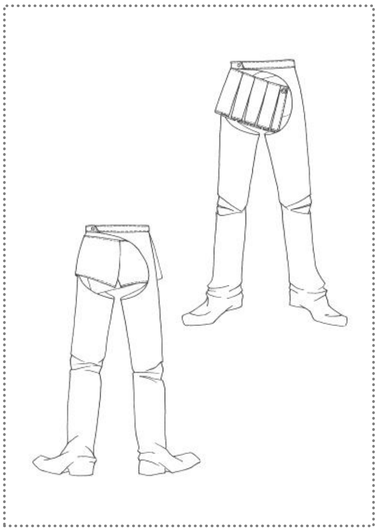
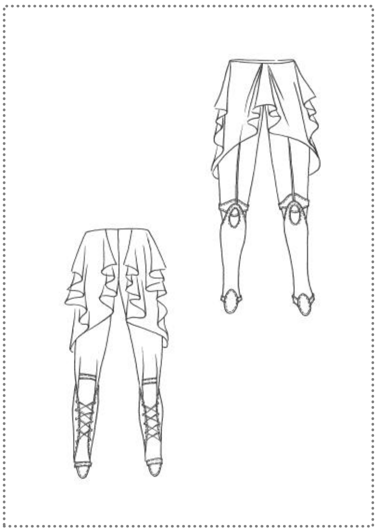
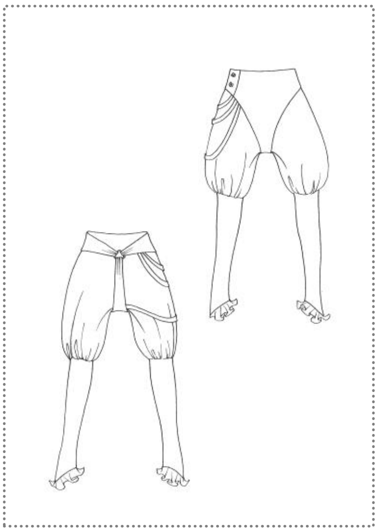
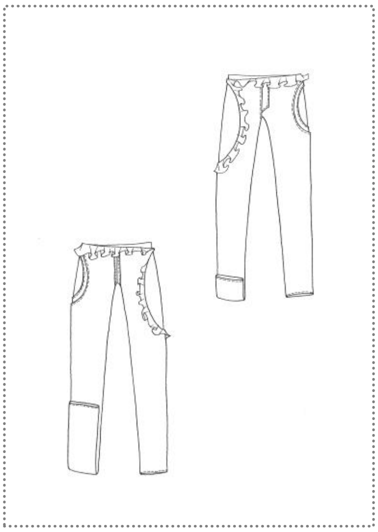
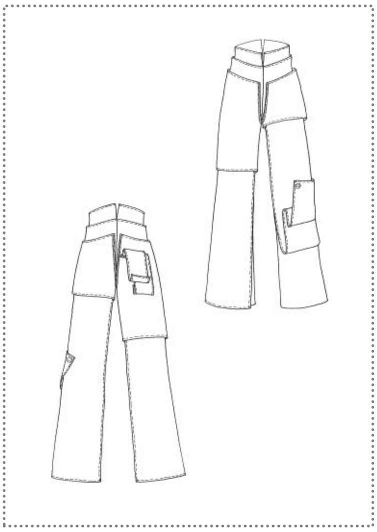
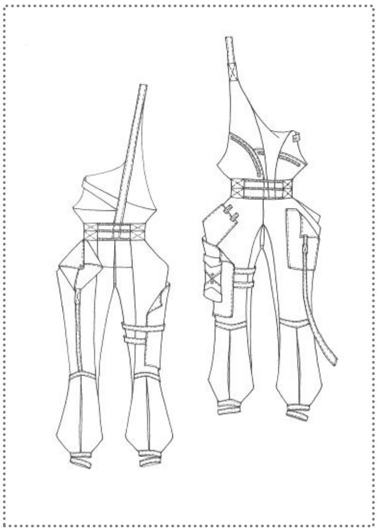
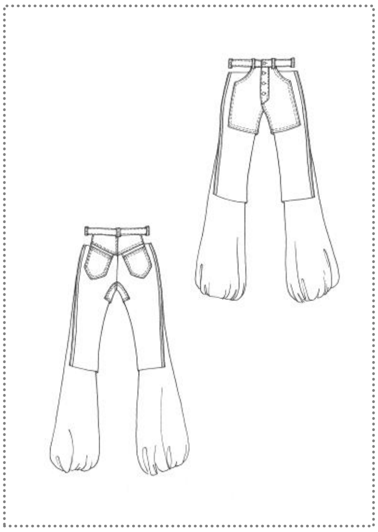
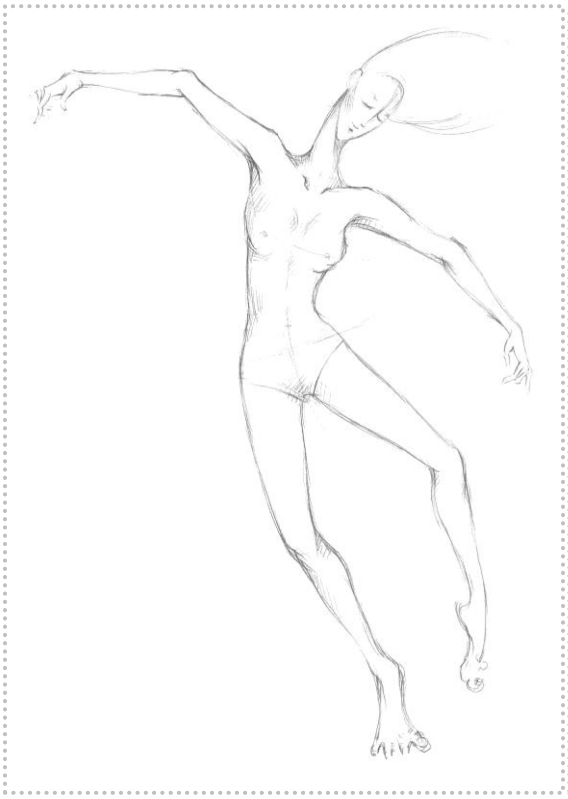










Figure B.6 23 ideas of trousers/dress in the form of working drawings

The successful styles of jackets/coats and trousers/dresses are selected from the working drawings and put together to form the wearing outfits on the dynamic human figures, as shown in Figures B.7 and B.8, with careful considerations to proportion, balance and rhythm. The most optimum collection has been collected and established in Appendix C.



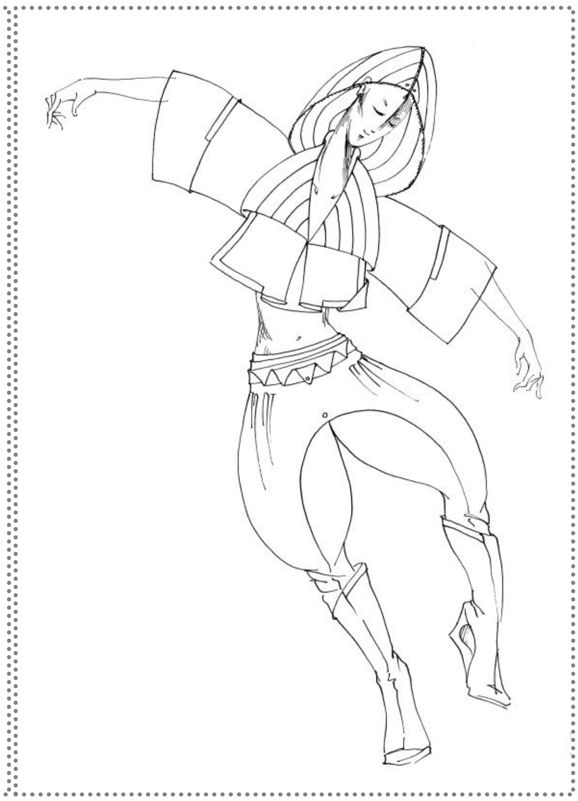
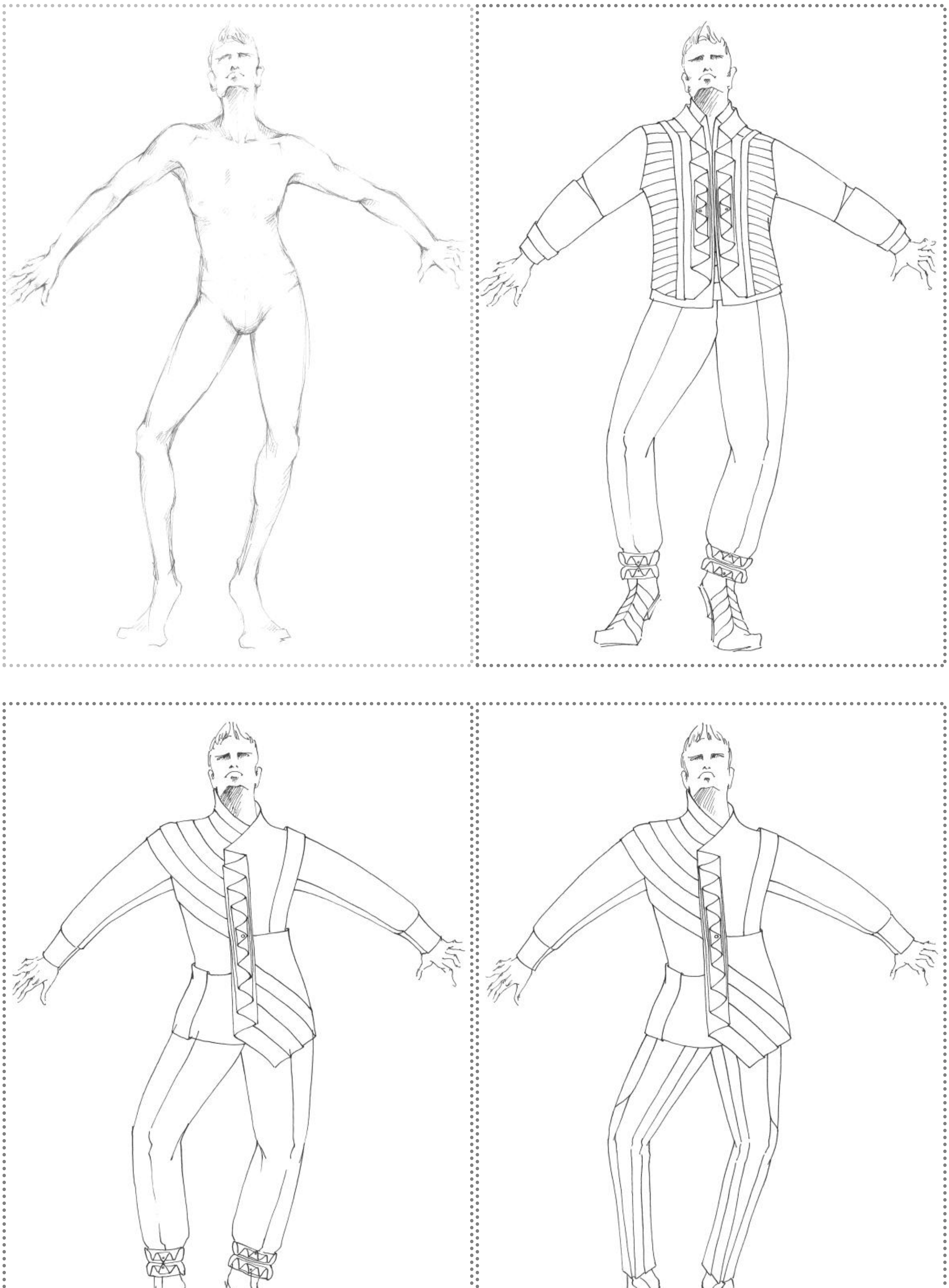



Figure B.7 A series of illustrations to compose the lady's outfits design on the dynamic human figures



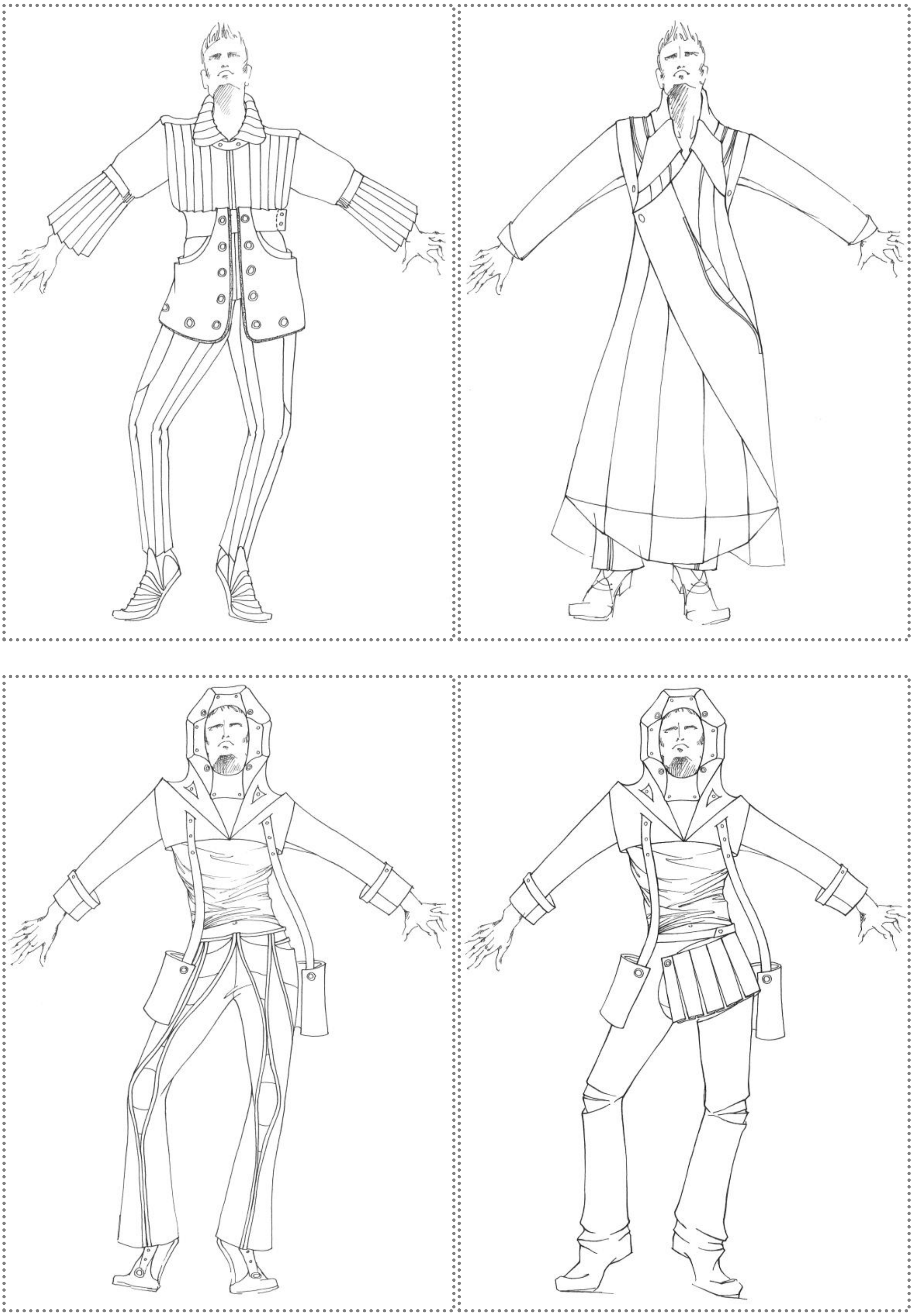


Figure B.8 A series of illustrations to compose the man's outfits design on the dynamic human figures

B.3 Initial Ideas for the Luminescent Innerwear Garment Design

The innerwear garment design is conceived with luminescent features. The structure and characteristic of the luminescent fabrics have been investigated, as shown in Figure B.9, with the careful manipulation and cutting considerations.

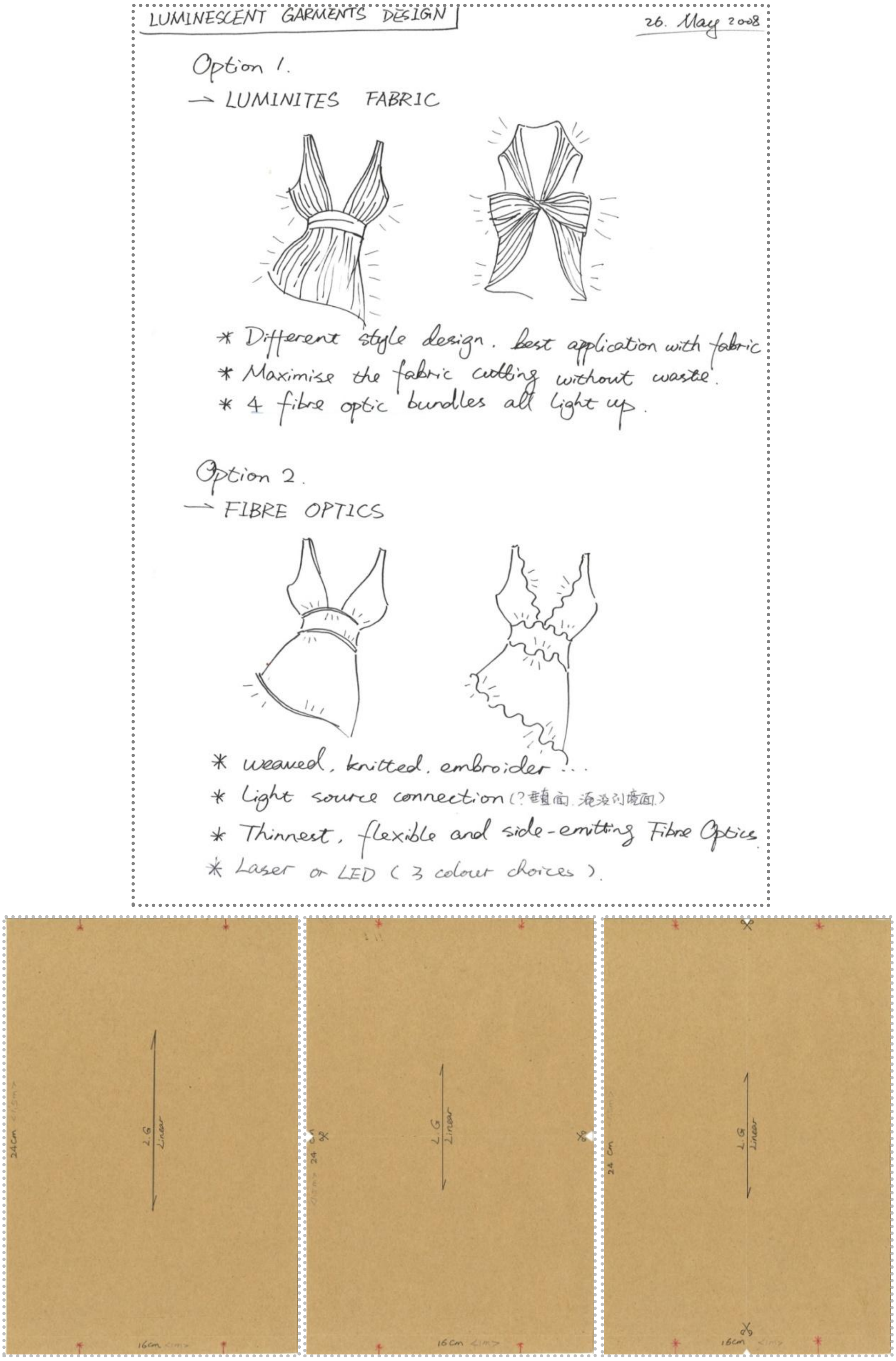
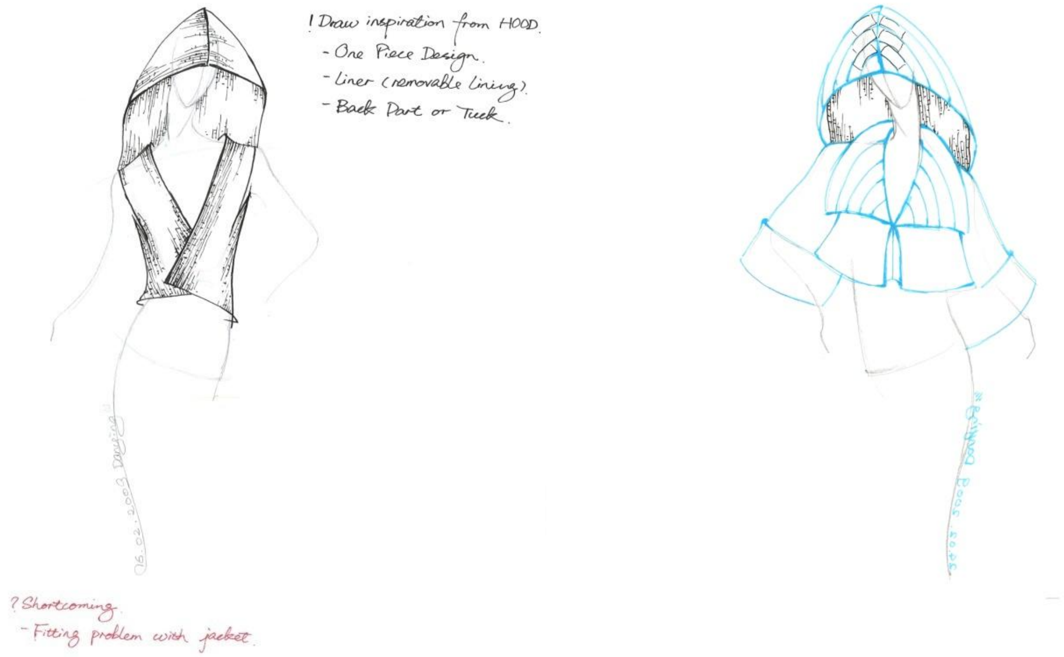
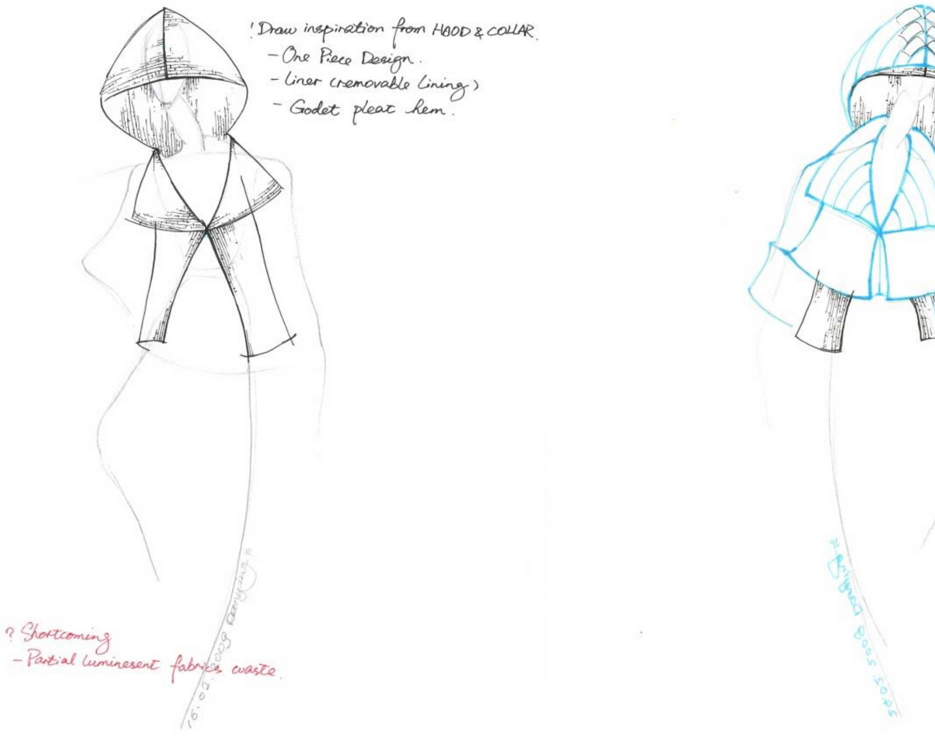


Figure B.9 Ideas and considerations to apply the luminescent fabrics in garment design

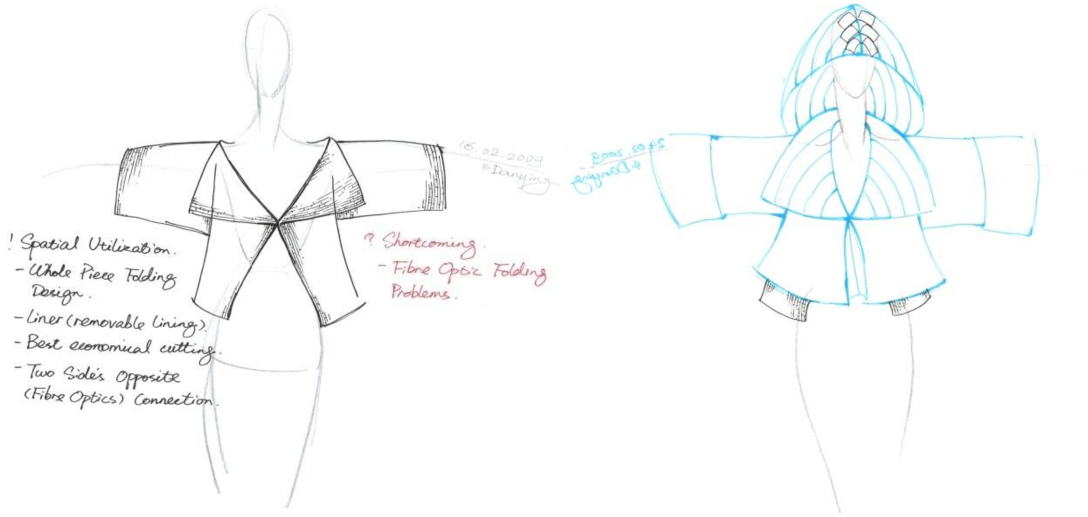
B.4 Innerwear Design Development

Paper folding methodology is considered, developed and modelled as stated in Chapter 4, with careful consideration of light continuity when cutting and folding the fabric piece. A series of designs have been created from models to sketches, and assembled with the outfits, as shown in Figure B.10. The optimum designs are presented in Appendix C after further development of toile modelling shown in Figures B.11 and B.12.

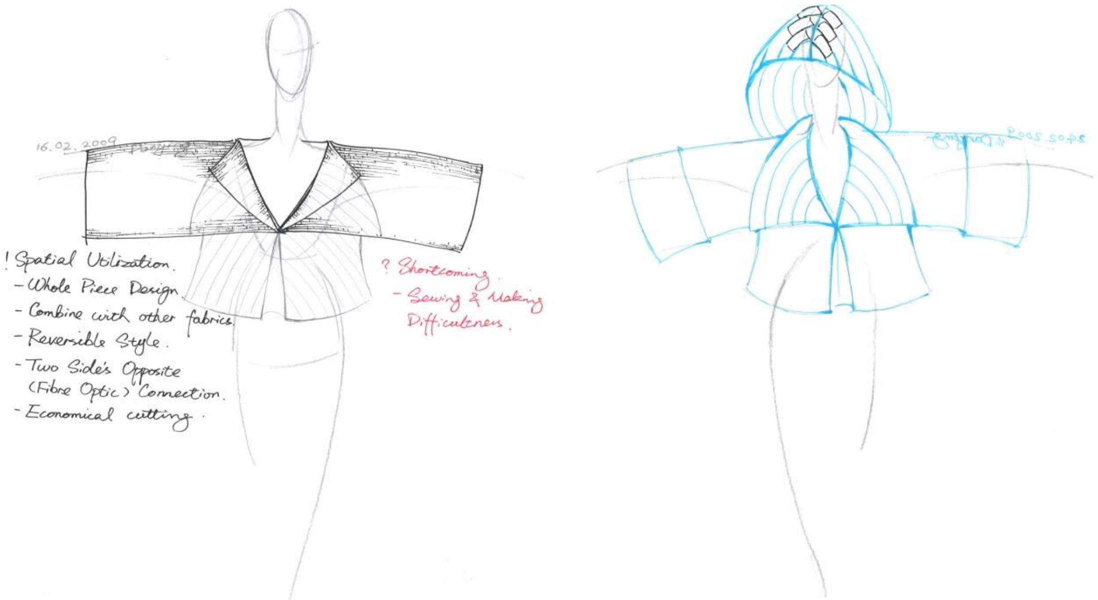


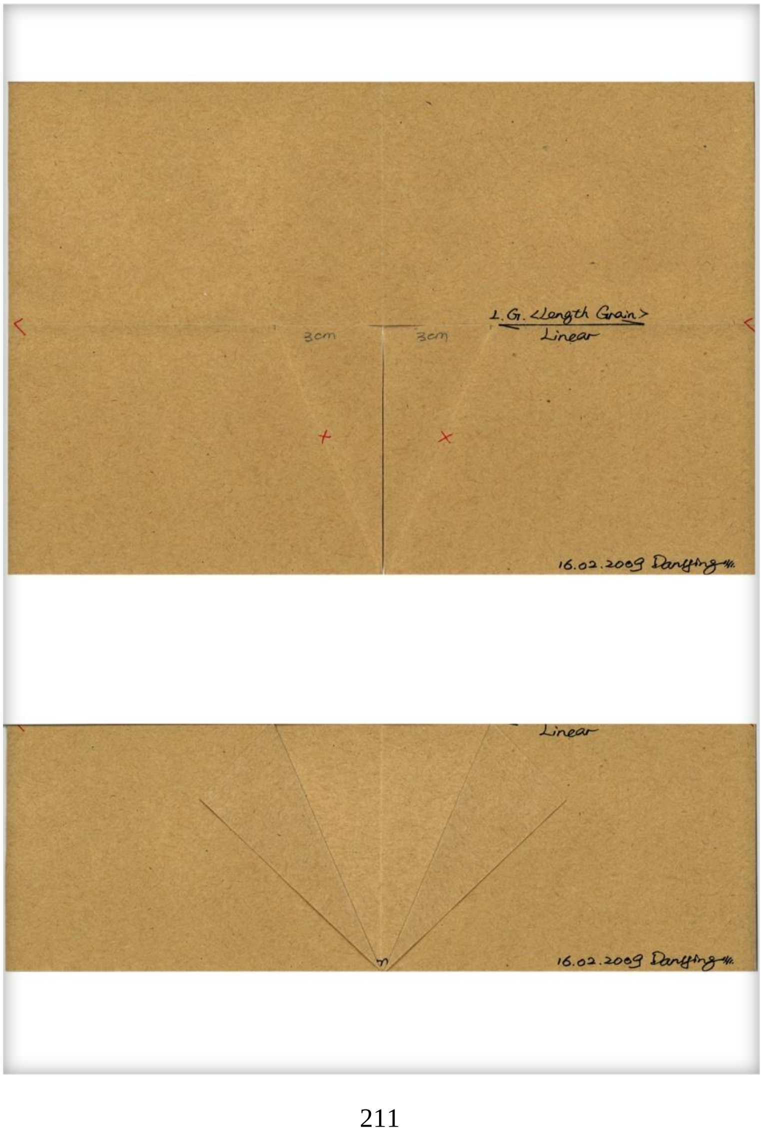

! Draw inspiration from HOOD & COLLAR.
- One Piece Design.
- Liner (removable Lining)
- Godet pleat hem.
? Shortcoming
- Partial luminescent fabrics waste.

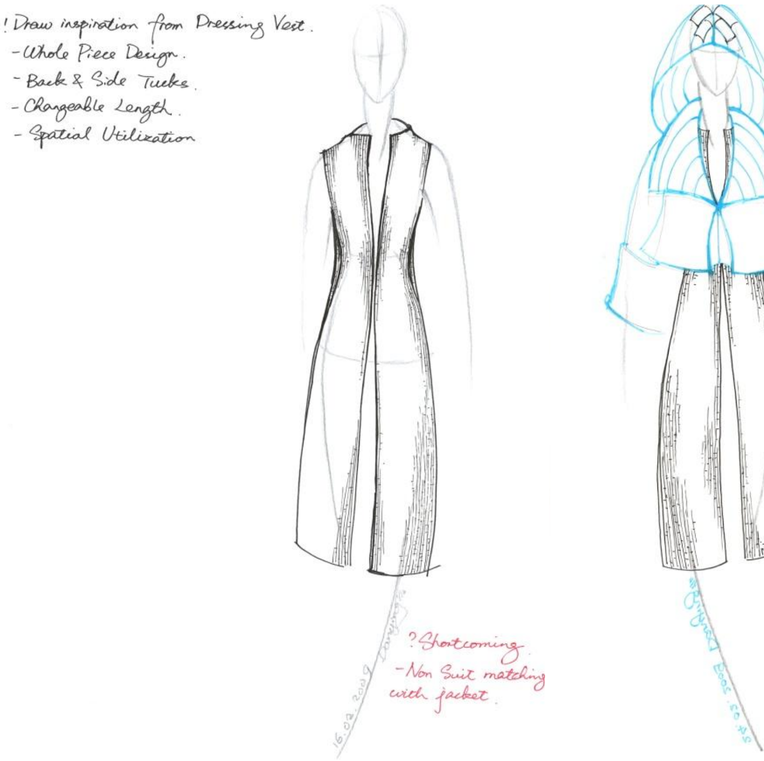

L.G.<Length Grain>
Linear
3.5cm
21cm
14cm


! Spatial Utilization.
- Whole Piece Folding Design.
- Liner (removable lining).
- Best economical cutting.
- Two Side's Opposite (Fibre Optics) Connection.
? Shortcoming.
- Fibre Optic Folding Problems.

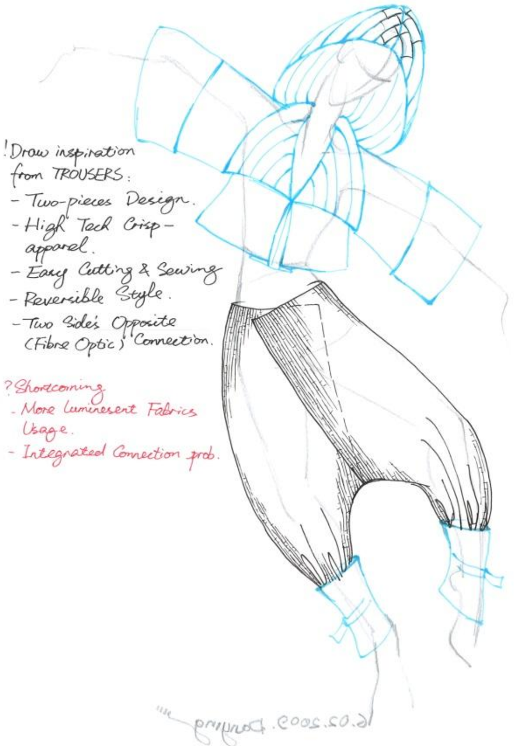

L.G. Length Grain
Linear
4.3cm
0.5cm
3.5cm
21cm


16.02.2009
! Spatial Utilization.
- Whole Piece Design
- Combine with other fabrics.
- Reversible Style.
- Two Side's Opposite
(Fibre Optic) Connection.
- Economical cutting.
? Shortcoming.
- Sewing & Making
Difficulteness.

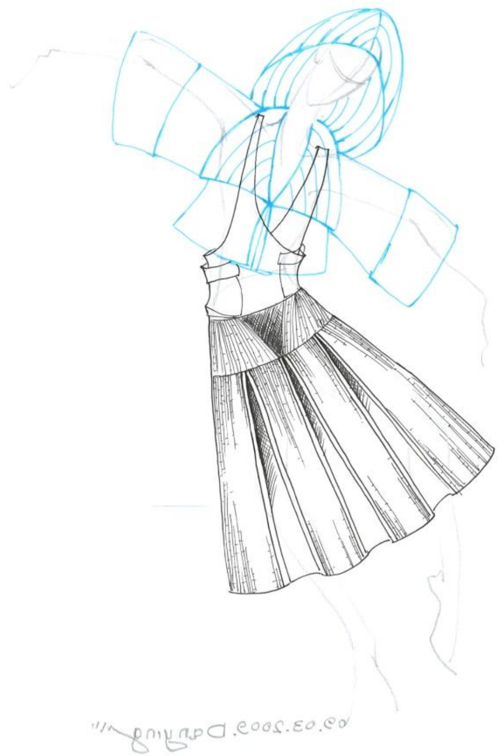

L.G. <Length Grain>
Linear
3cm
3cm
16.02.2009
Linear
16.02.2009

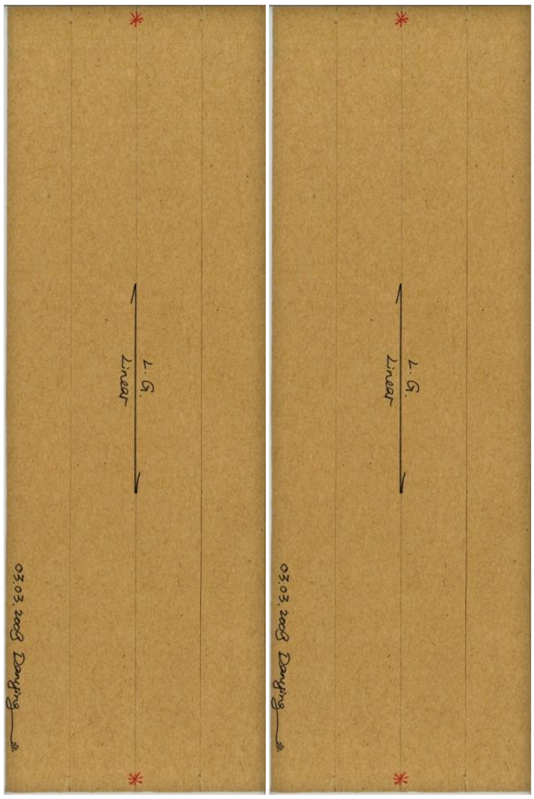

! Draw inspiration from Dressing Vest.
- Whole Piece Design.
- Back & Side Tucks.
- Changeable Length.
- Spatial Utilization
? Shortcoming.
- Non Suit matching with jacket.

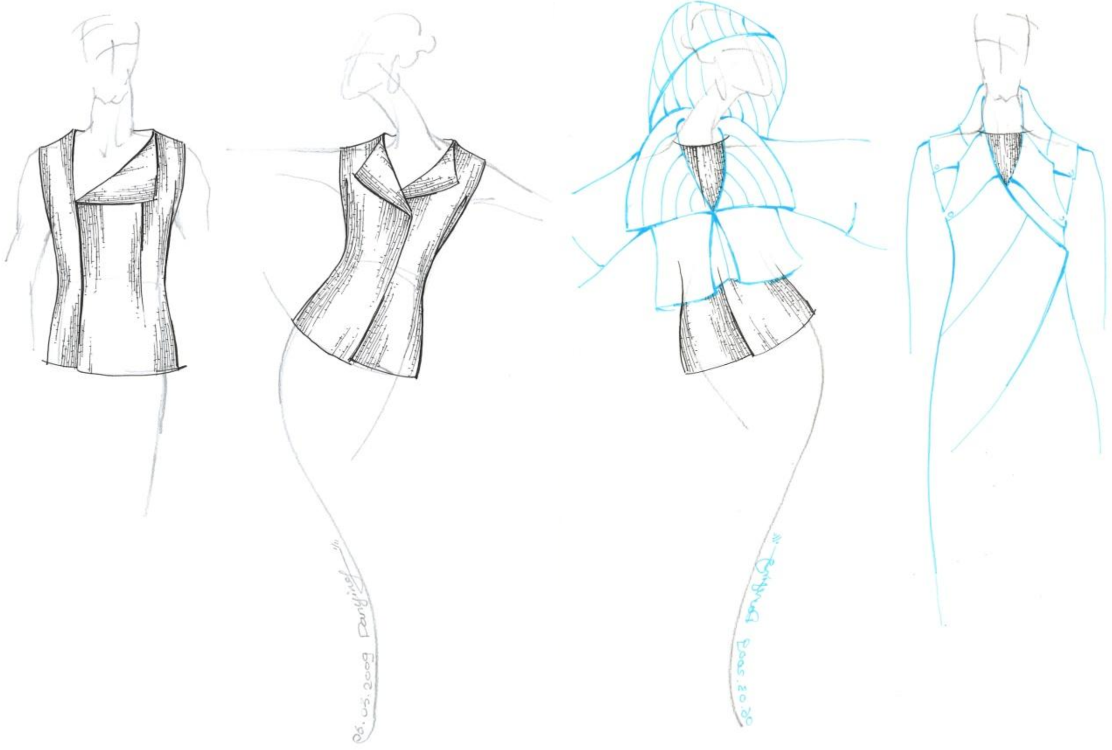

14cm
L.G. <Length Grain>
Linear
21cm


!Draw inspiration from TROUSERS:
- Two-pieces Design.
- High Tech Crisp-apparel.
- Easy Cutting & Sewing
- Reversible Style.
- Two Side's Opposite (Fibre Optic) Connection.
?Shortcoming
- More Luminesent Fabrics Usage.
- Integrated Connection prob.


14cm
14cm
Linear

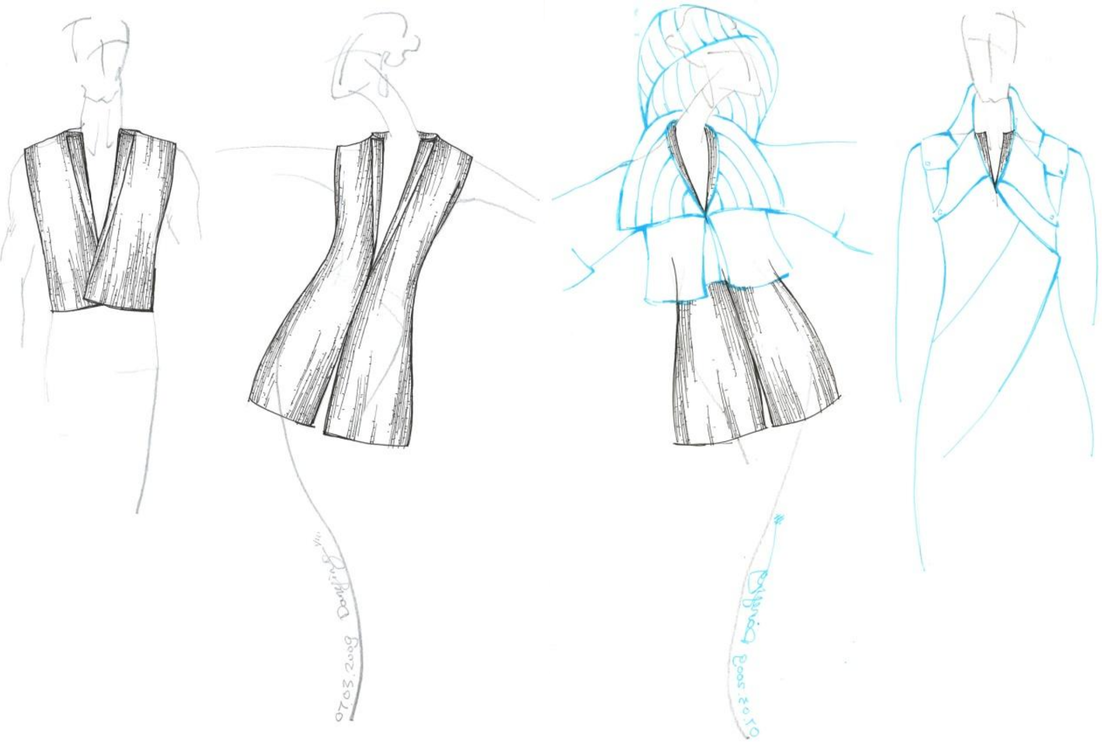



L.G.
Linear
L.G.
Linear




2cm
4cm
L. G.
Linear
8cm
03.03.2009 Danjing


2cm
4cm
L. G.
Linear
8cm
03.03.2009 Danjing




4cm
4cm
5.5cm
5.5cm
L.G.
Linear
03.03.2009 Danying


5cm
3cm
4cm
L.G.
Linear
03.03.2009 Danying

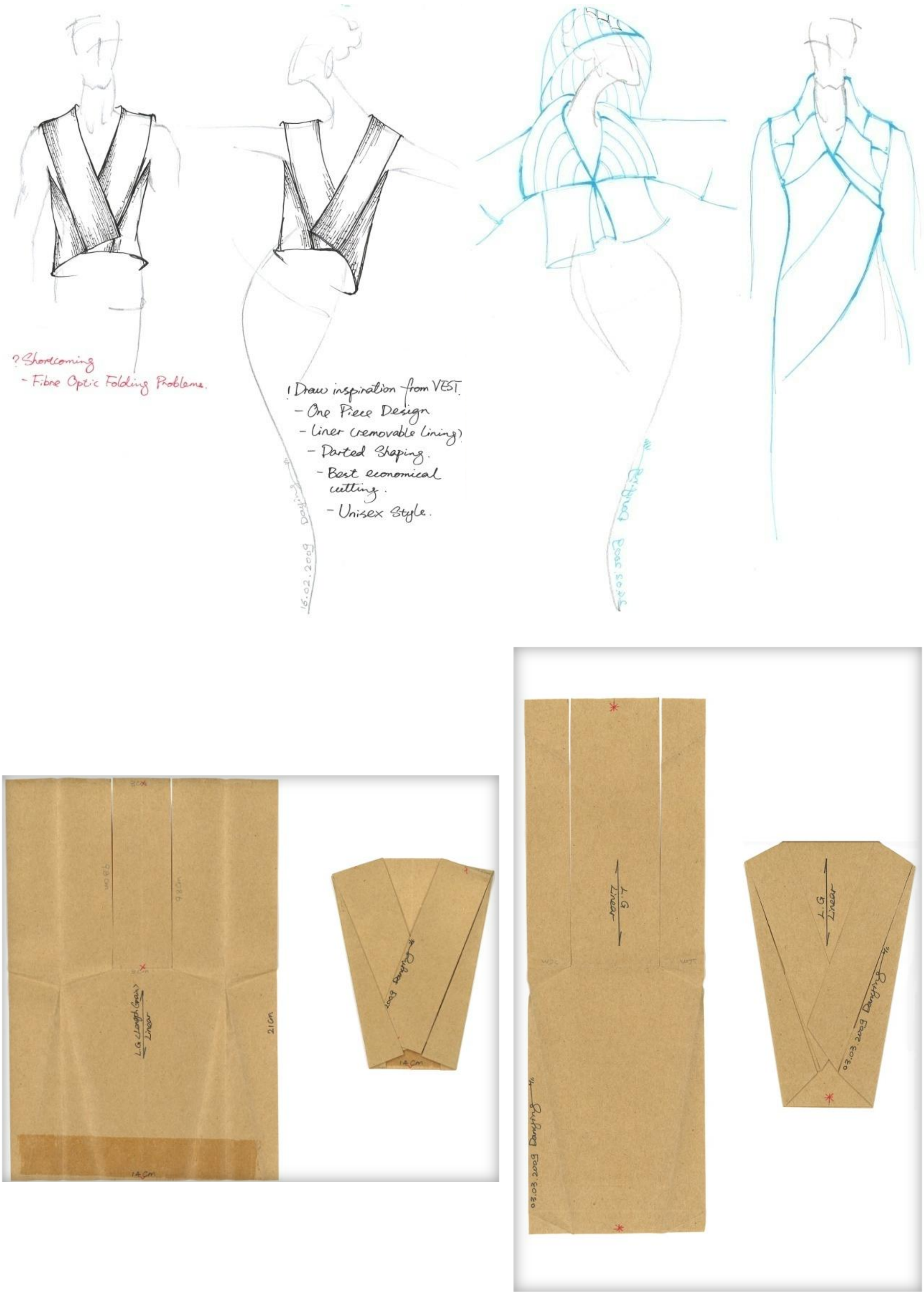


Figure B.10 A series of paper folding models to develop the innerwear garment design – Womenswear and menswear


12
40
208

Figure B.11 A series of toile modelling samples to further develop the lady's innerwear design – Front, side and back views

Figure B.12 A series of toile modelling samples to further develop the man's innerwear design – Front, side and back views

APPENDIX C – PRESENTATION OF THE SMART CLOTHING COLLECTION

Based on the work presentation in Appendix B, the final fashionable SMART clothing designs have been created as a collection. They consist of five suits, three for ladies and two for men. Two of the suits, one for a lady and another for a man, has been successfully made up and presented in this appendix.

According to the project theme *"Power the Mode, Light the Mood"*, the SMART clothing collection is sketched in Figure C.1.

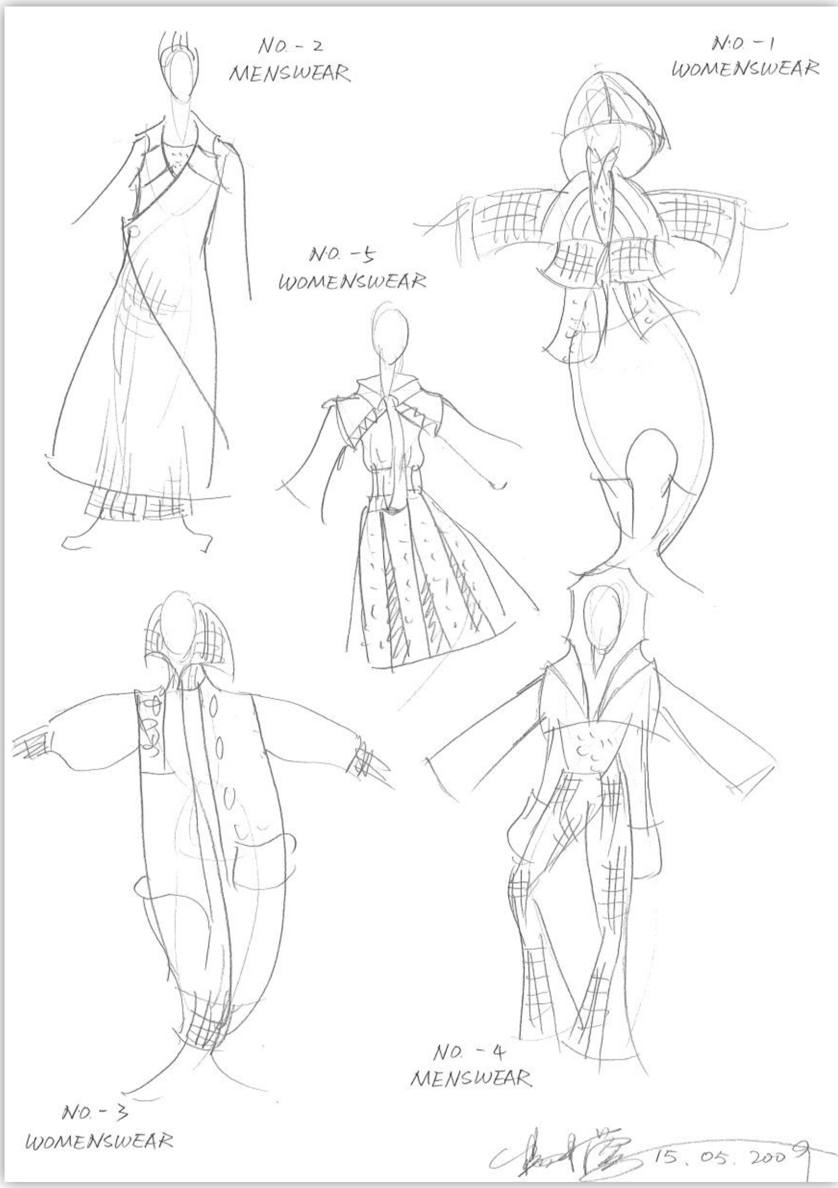


Figure C.1 SMART clothing collection – "Power the Mode, Light the Mood"

C.1 Styles with Details

Figures C.2 – C.6 illustrate the five styling suits of the best silhouette, proportionality and rhythm designs created in Appendix B.

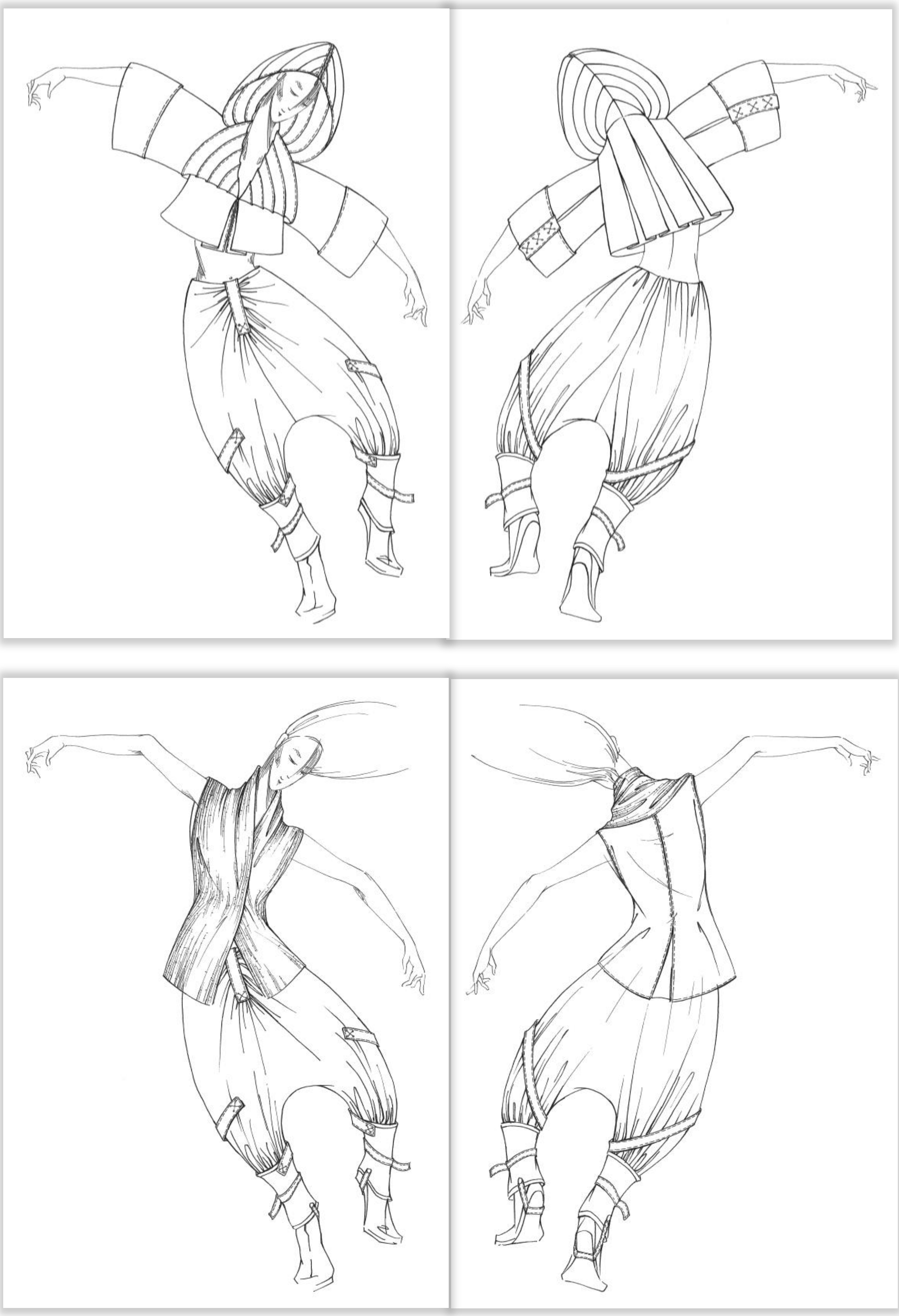


Figure C.2 Illustrations of style No.1 – Womenswear with front and back views

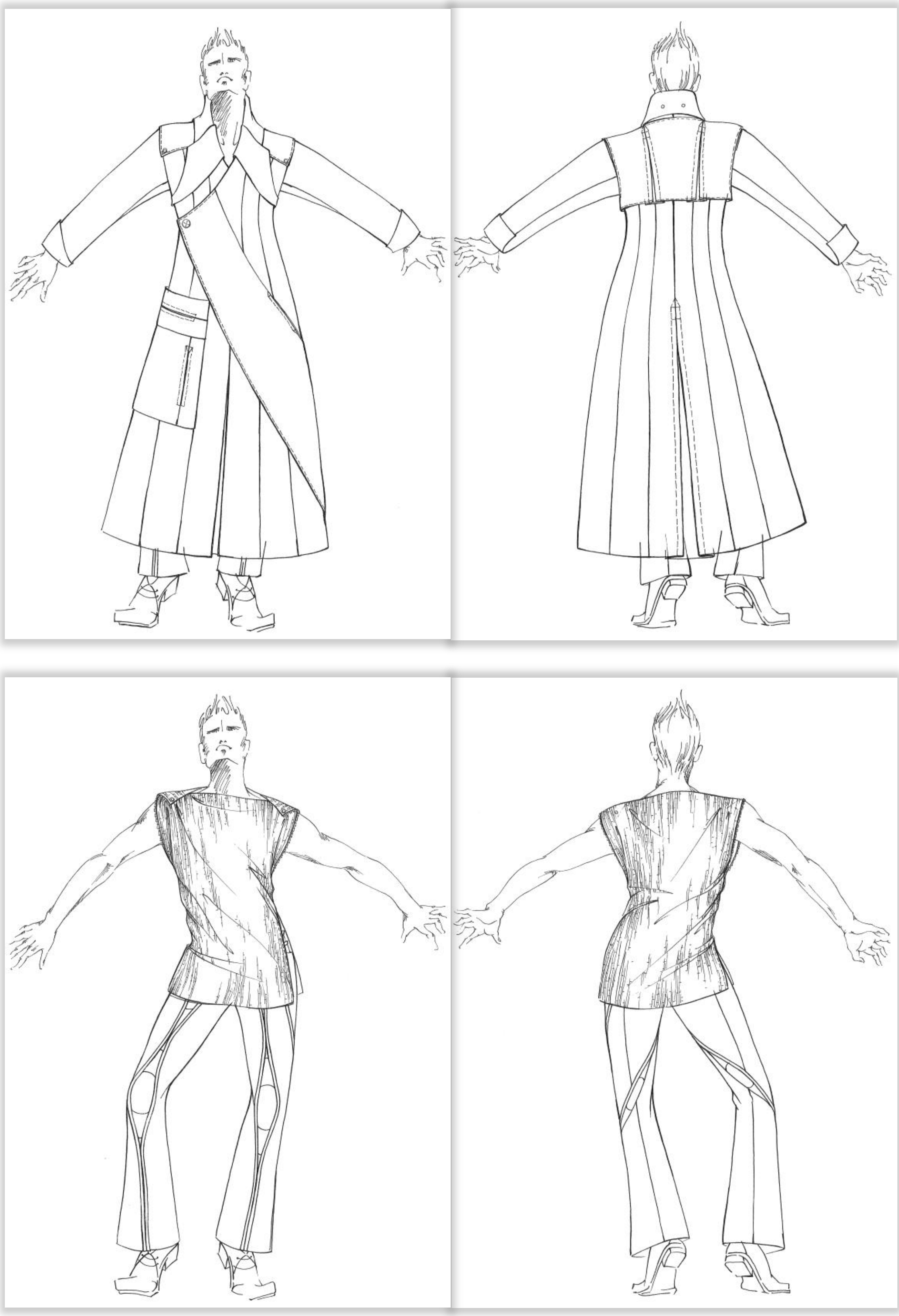


Figure C.3 Illustrations of style No.2 – Menswear with front and back views

Figure C.4 Illustrations of style No.3 – Womenswear with front and back views

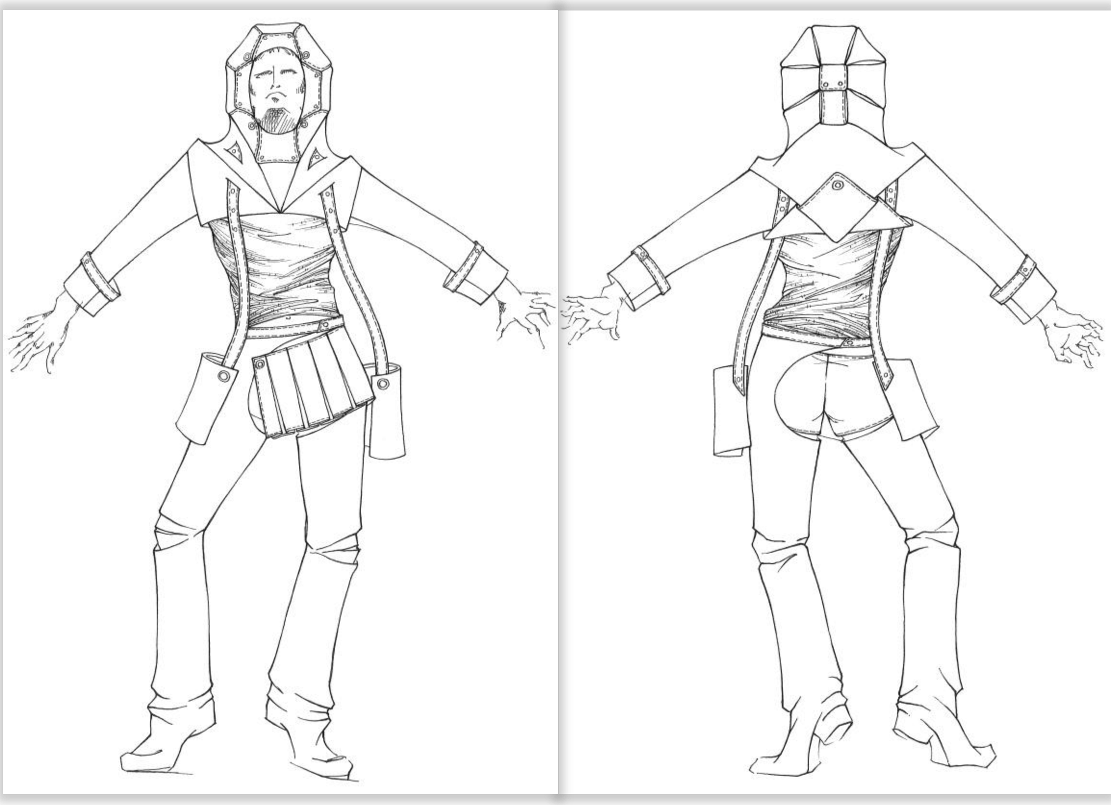


Figure C.5 Illustrations of style No.4 – Menswear with front and back views

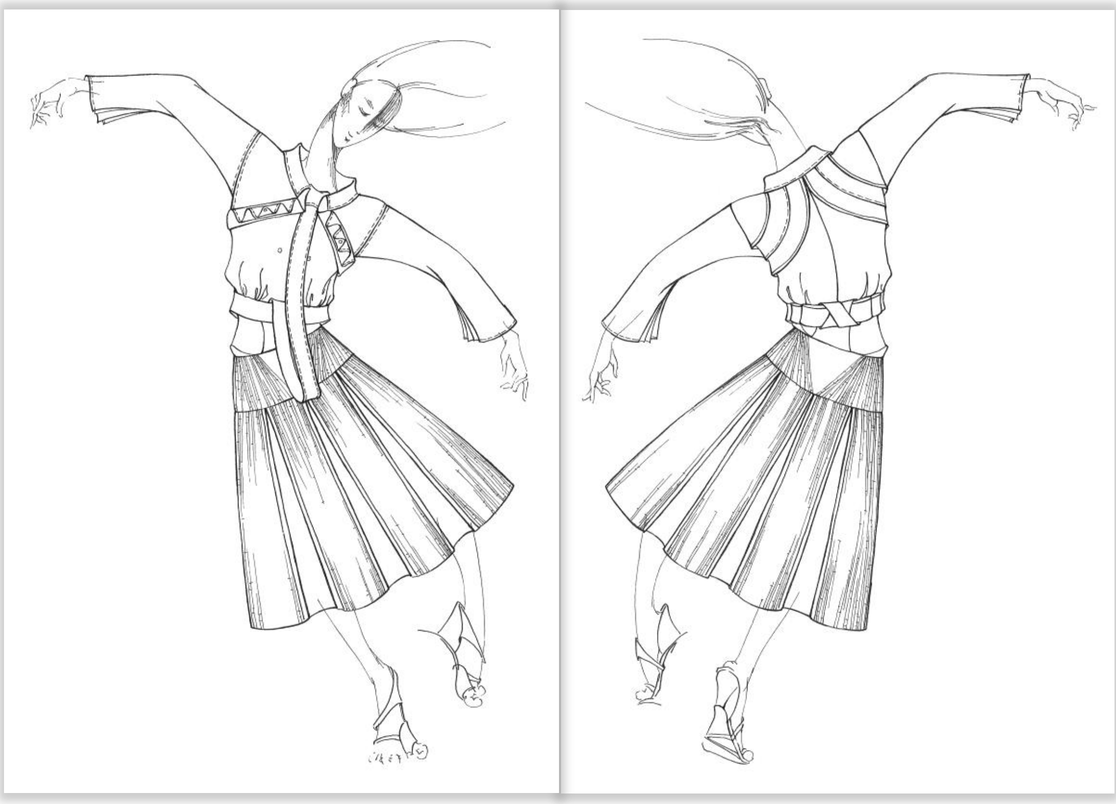


Figure C.6 Illustrations of style No.5 – Womenswear with front and back views

C.2 Colour Specification

The achromatic colour scheme, shown in Figure C.7, is used in the outerwear garment design which contains the black and white grid-patterned PV panels.

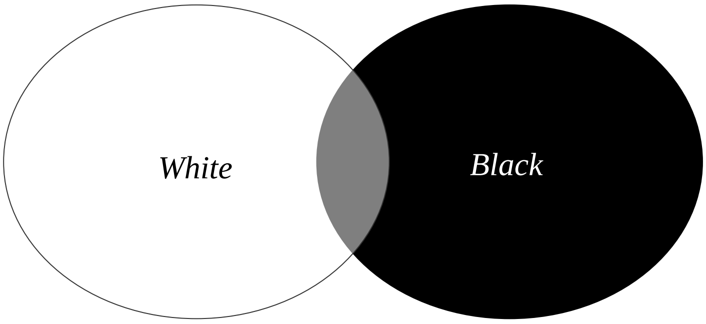


Figure C.7 Black and white hue in different textures

A diverse RGB colour scheme, Figure C.8, is applied in the innerwear garment design which contains luminescent fabrics.

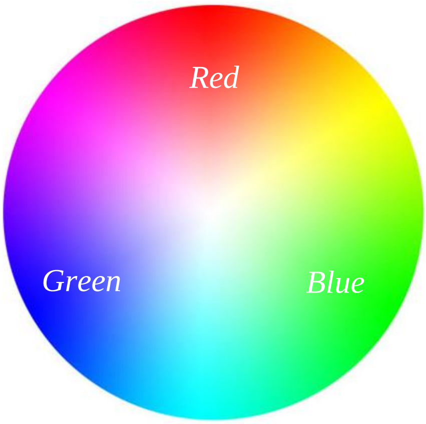


Figure C.8 RGB colours via light mixtures

C.3 Fabric Samples

Traditional silk, waxed cotton and tartan fabrics, technical PVC and Gore-Tex fabrics are chosen to blend with the photovoltaic films in the outerwear garment design, whilst chiffon and cotton lining fabrics are used to combine with the luminescent fabrics of the innerwear garment design, as shown in Figure C.9.

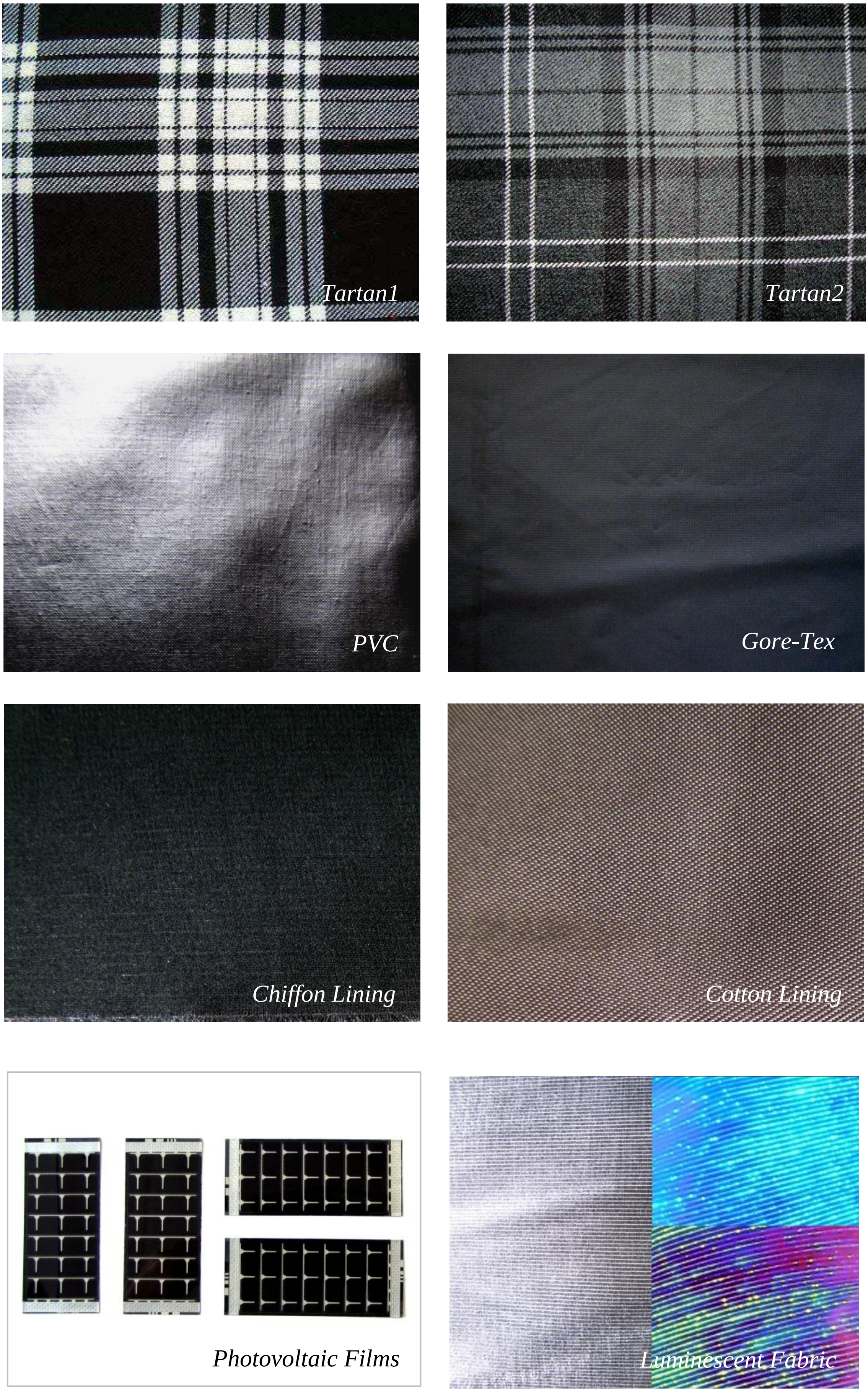


Figure C.9 Fabrics/materials combination

C.4 Outfits' Collection

The full and final design collection of the five chosen outfits is illustrated in Figures C.10 – C.19.

Figure C.10 Final illustration of style No.1 – Lady's energy harvesting suit

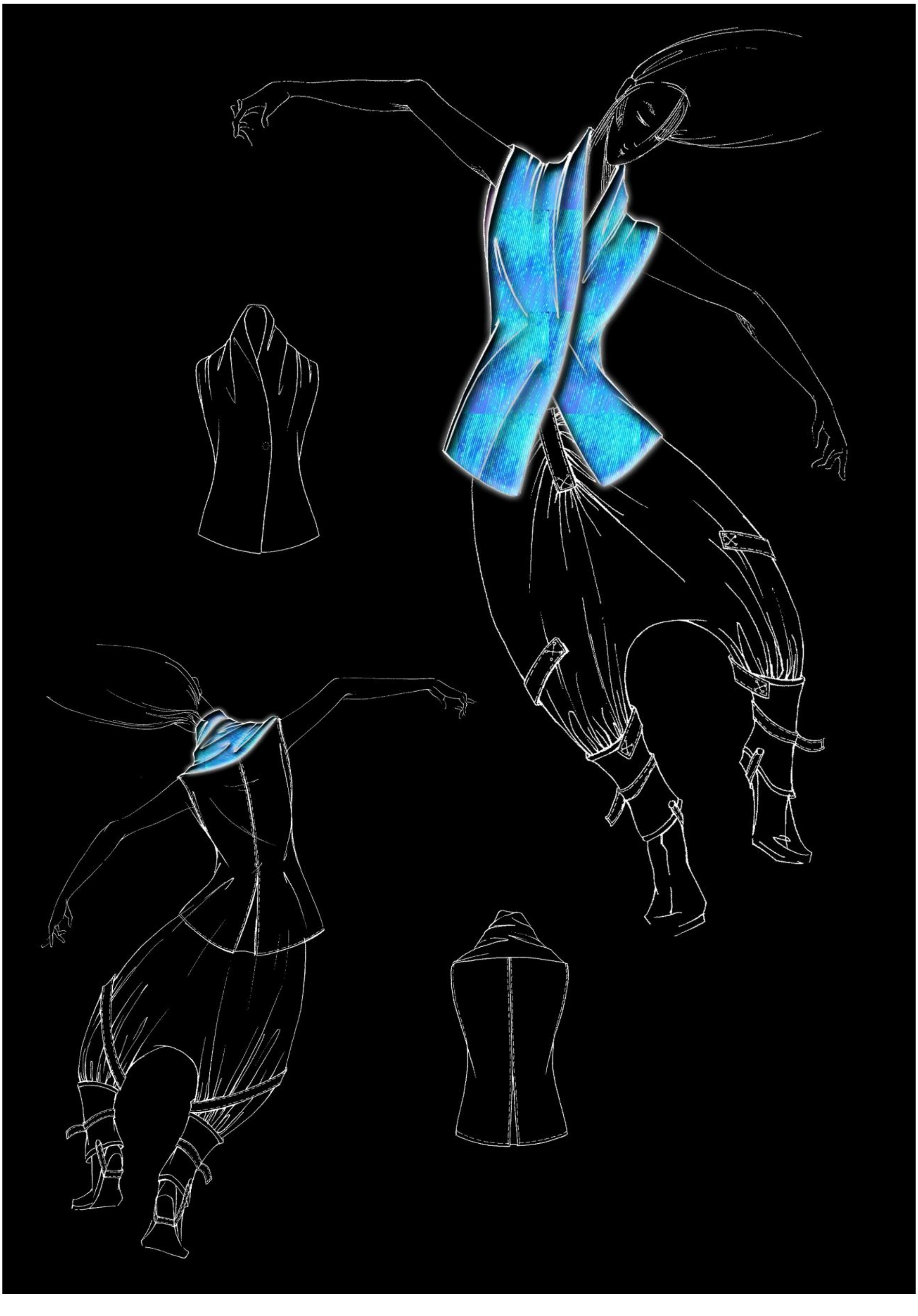
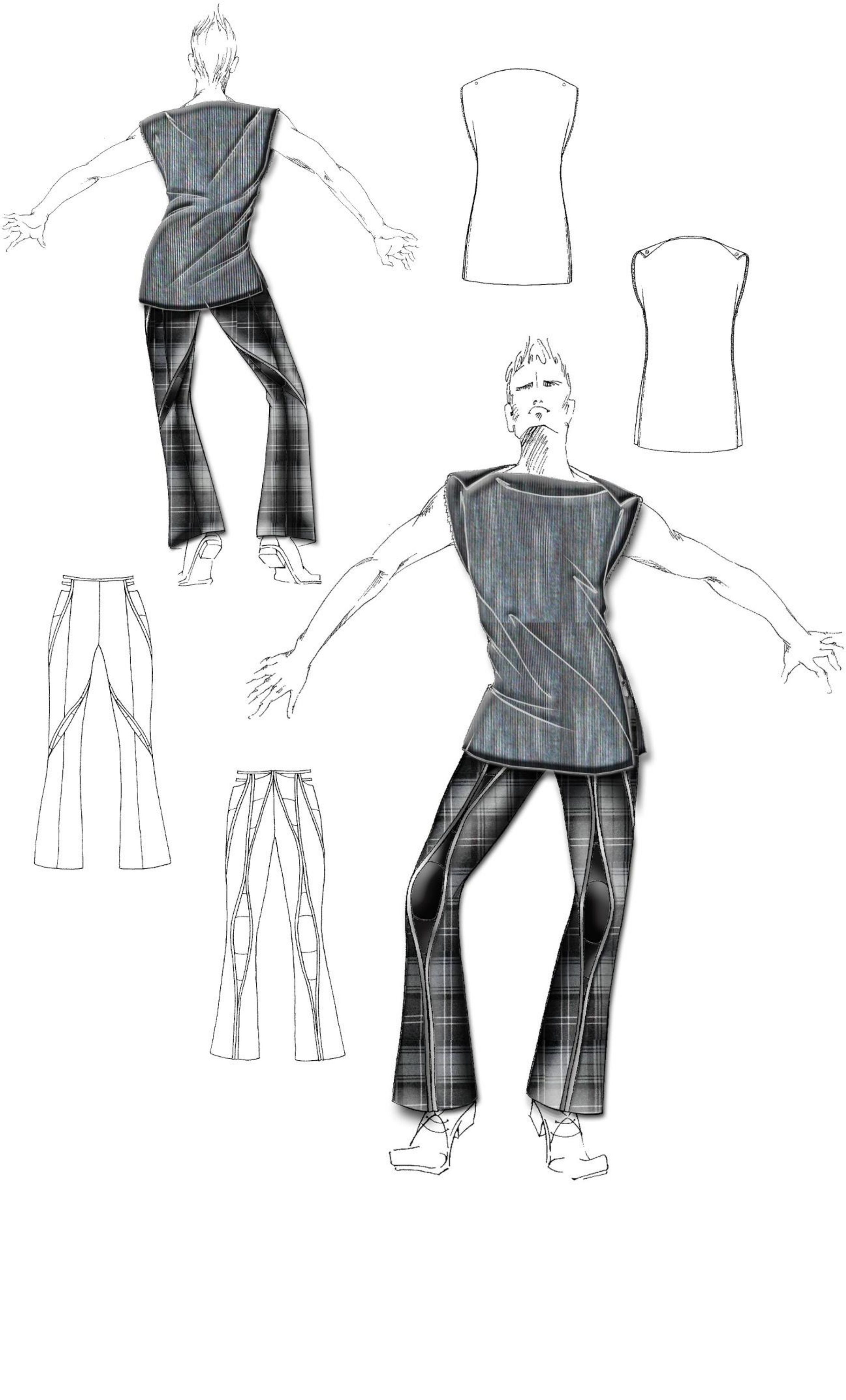


Figure C.11 Final illustration of style No.1-1 – Lady's mood changing suit

Figure C.12 Final illustration of style No.2 – Man's energy harvesting suit



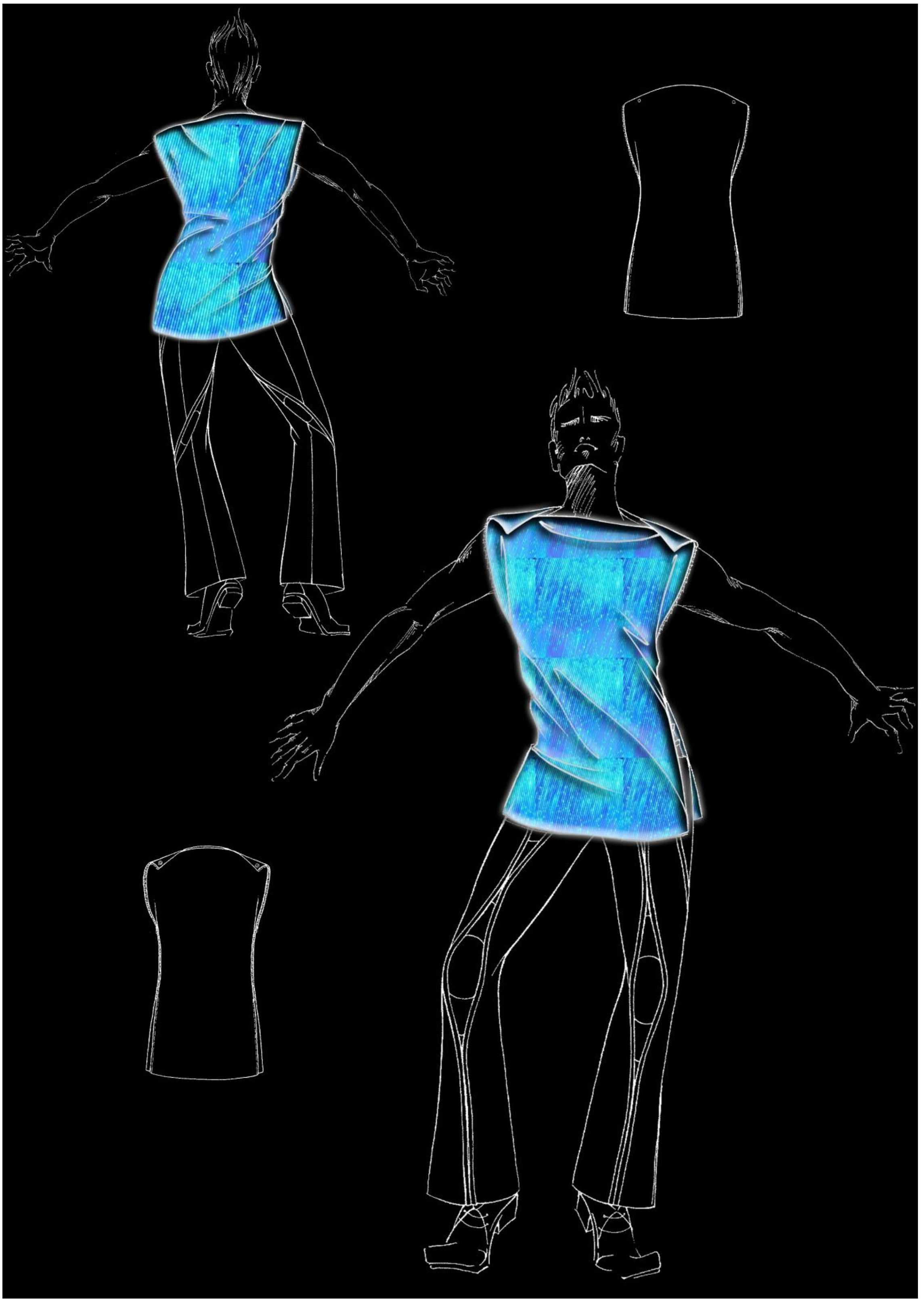


Figure C.13 Final illustration of style No.2-1 – Man's mood changing suit

Figure C.14 Final illustration of style No.3 – Lady's energy harvesting suit

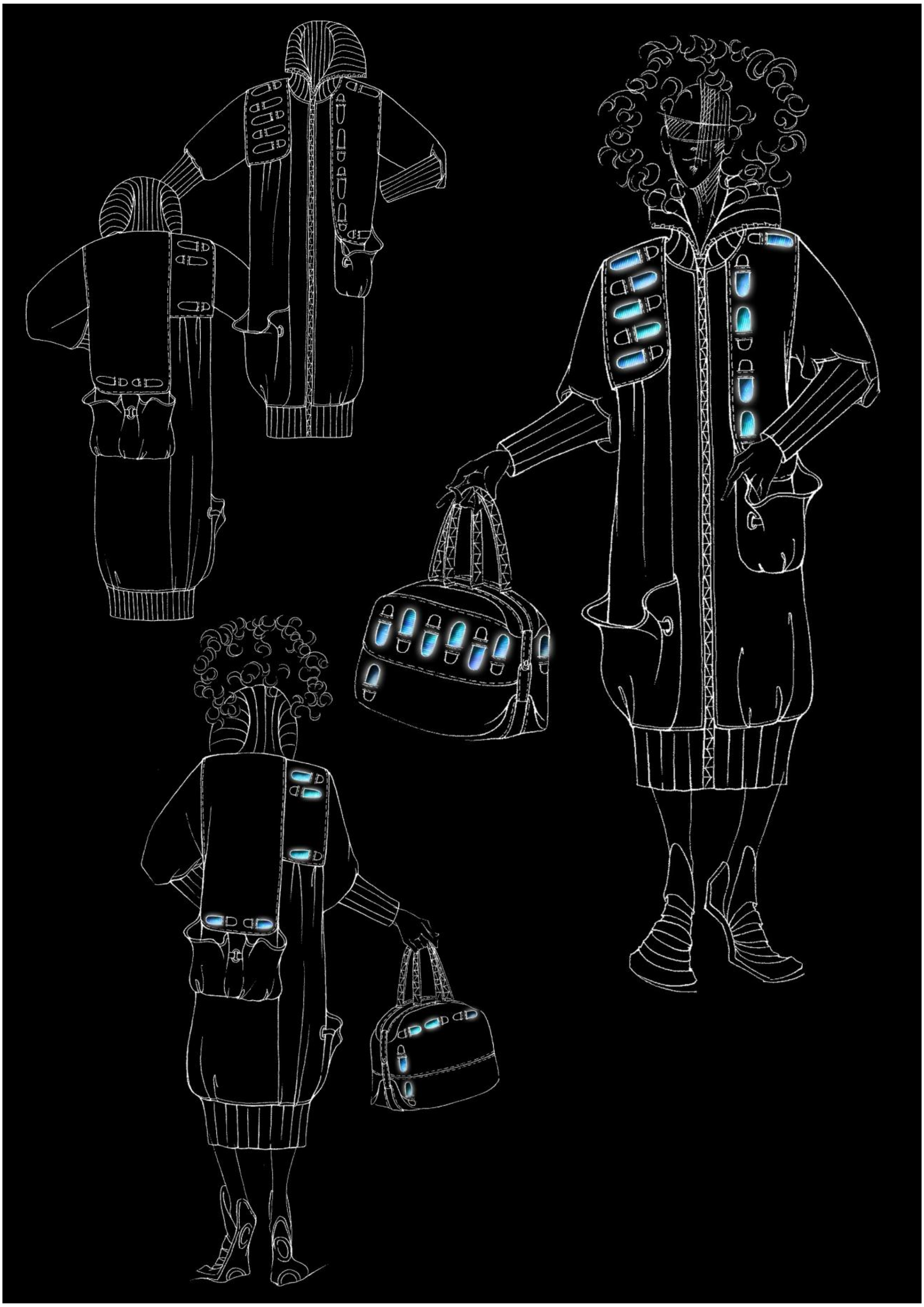


Figure C.15 Final illustration of style No.3-1 – Lady's mood changing suit

Figure C.16 Final illustration of style No.4 – Man's energy harvesting suit

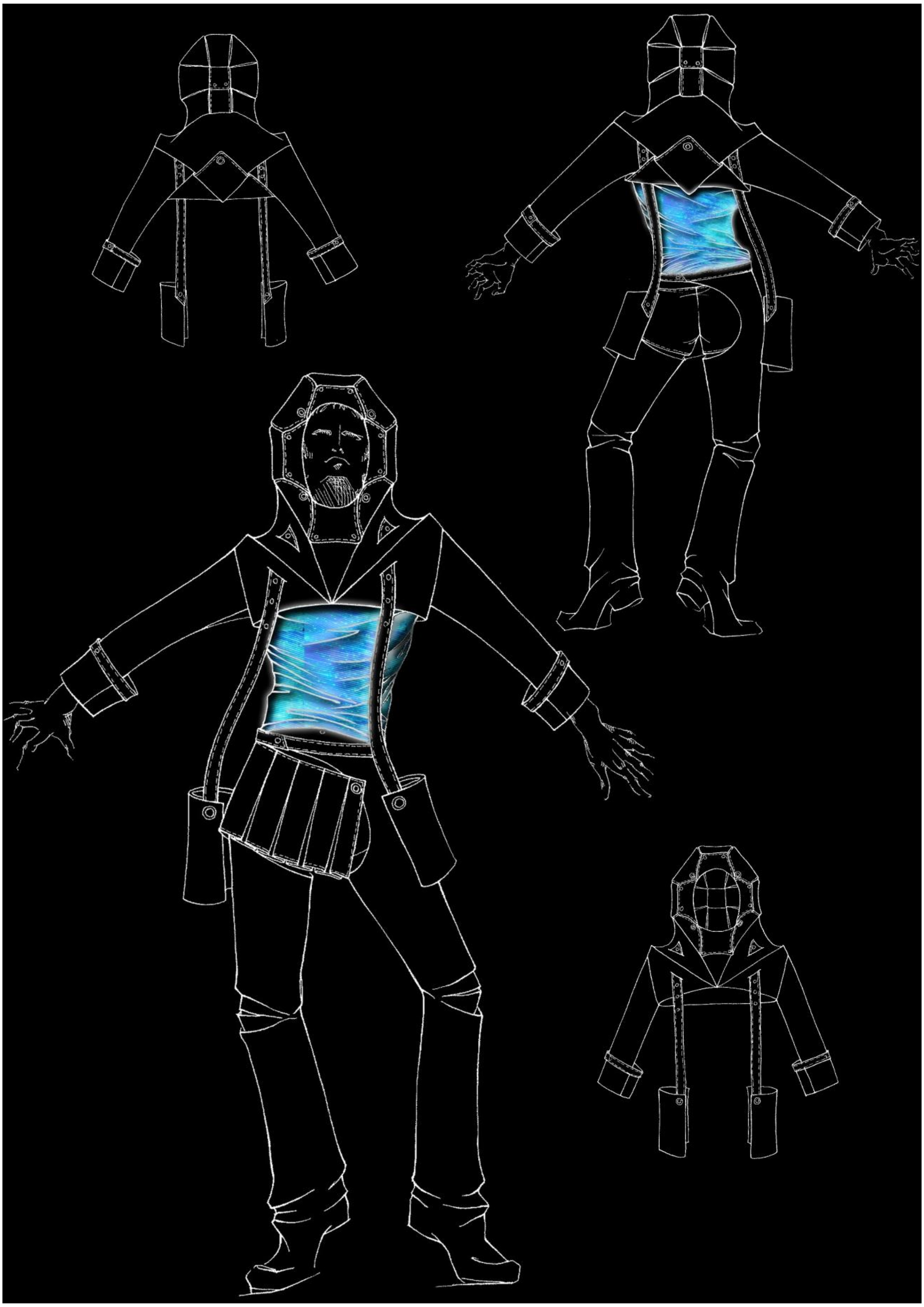


Figure C.17 Final illustration of style No.4-1 – Man's mood changing suit

Figure C.18 Final illustration of style No.5 – Lady's energy harvesting suit

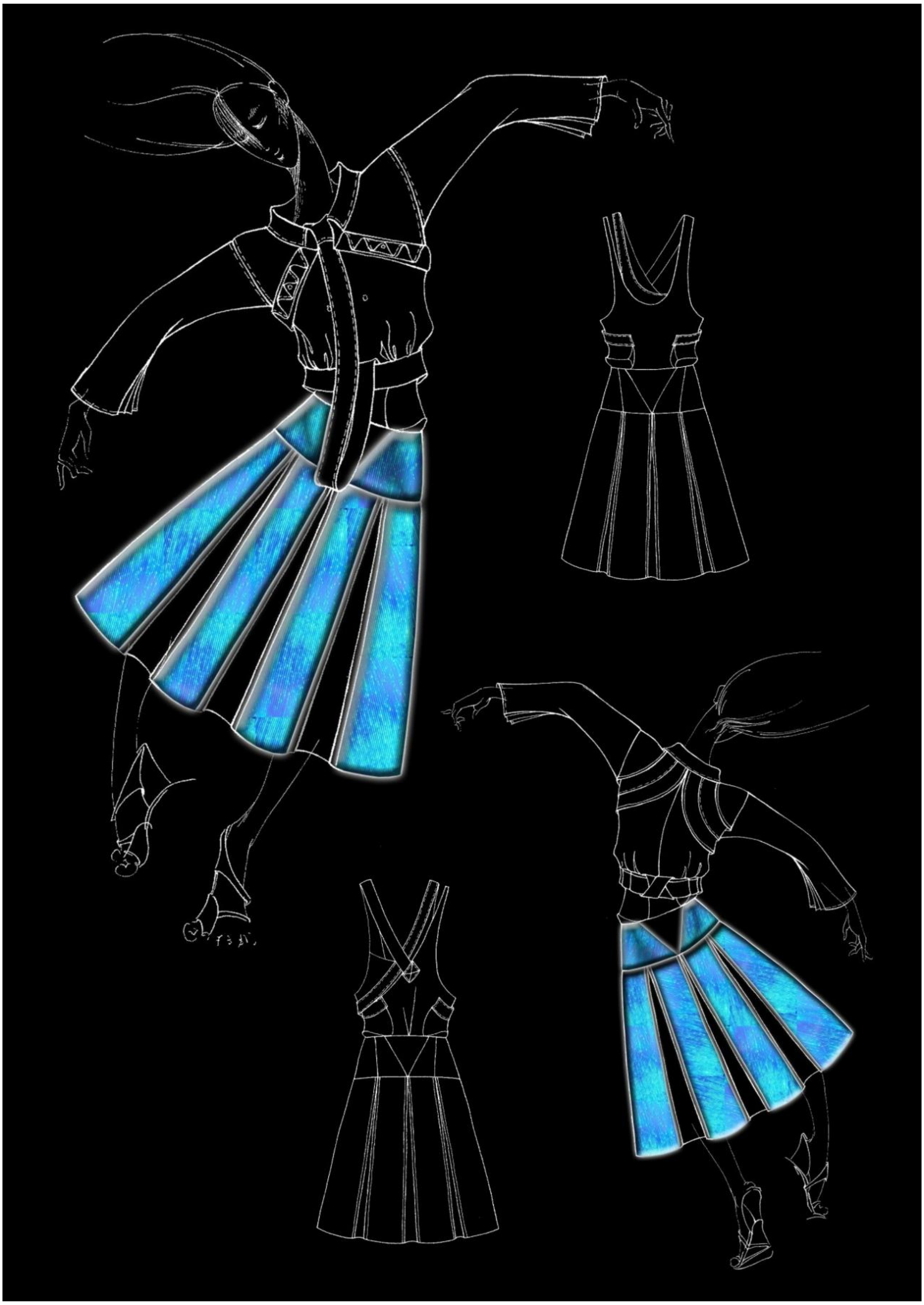


Figure C.19 Final illustration of style No.5-1 – Lady's mood changing suit

C.5 Prototypes Presentation

With careful design and technology implementation, styles No.1 and No.2 are made up as shown in Figure C.21, along with two energy harvesting pouch accessories shown in Figure C.20.

Figure C.20 Energy harvesting pouches as clothing accessories

Figure C.21 SMART clothing Prototypes - Styles No.1 and No.2

The collection of SMART energy harvesting and mood changing clothing is presented in Figures C.22 – C.26, at different angles with coloured lighting effect. A live CD is attached to show this collection in real time on human models.

Figure C.22 Presentation of the SMART energy harvesting clothing collection – At different angles

Figure C.23 Presentation of the SMART mood changing clothing collection – At different angles

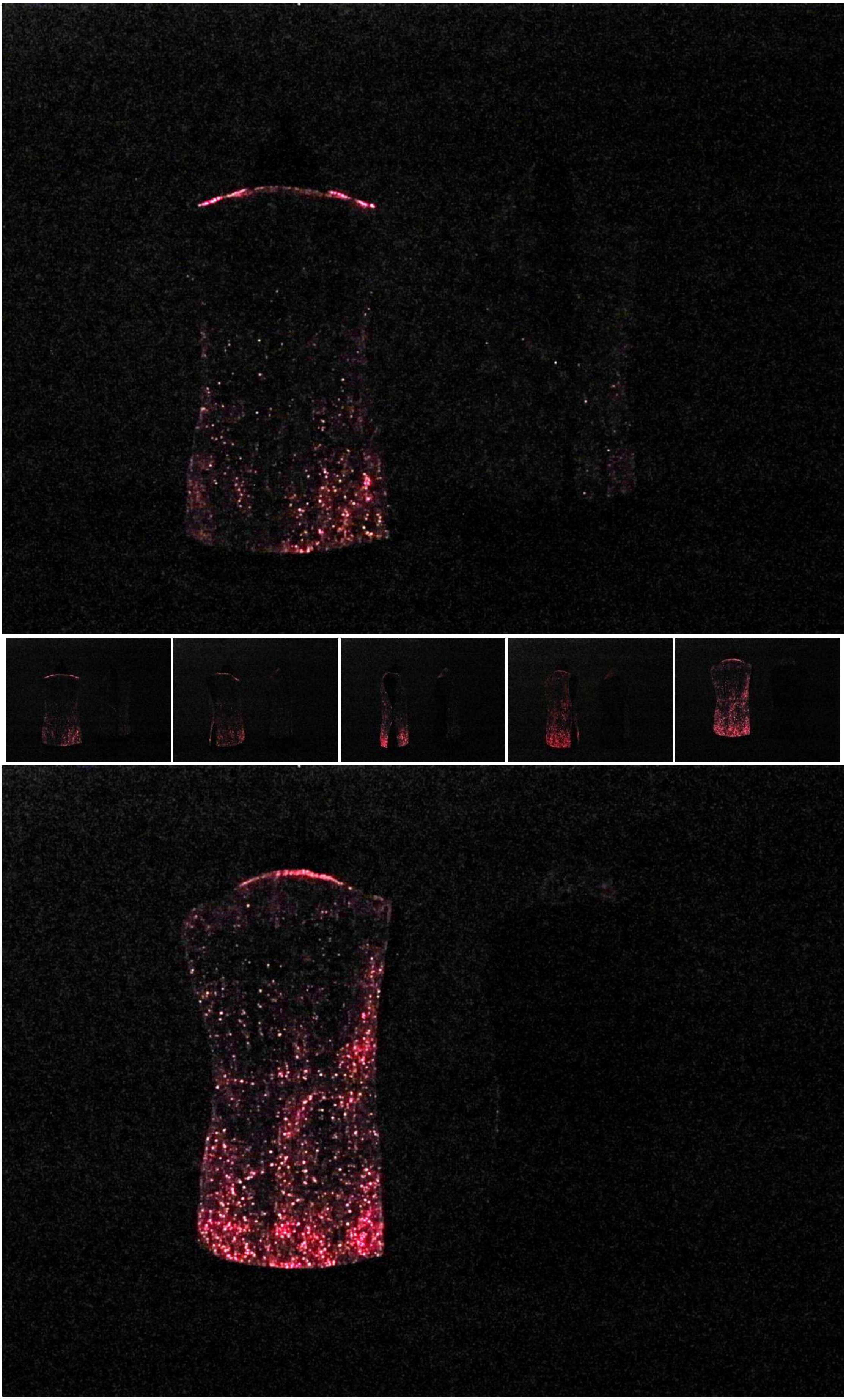


Figure C.24 Presentation of the SMART mood changing clothing collection – Red lighting effect at different angles

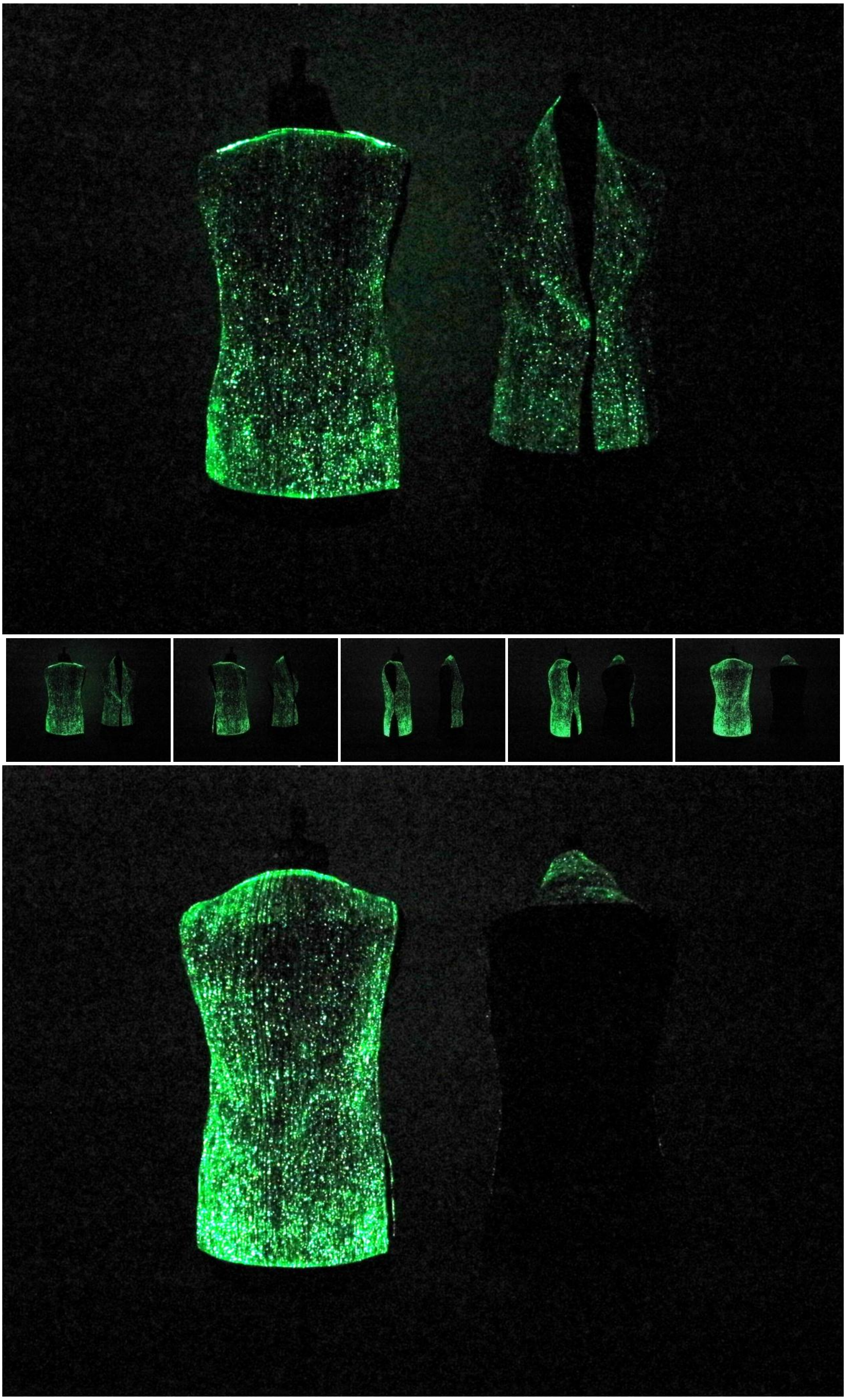


Figure C.25 Presentation of the SMART mood changing clothing collection – Green lighting effect at different angles

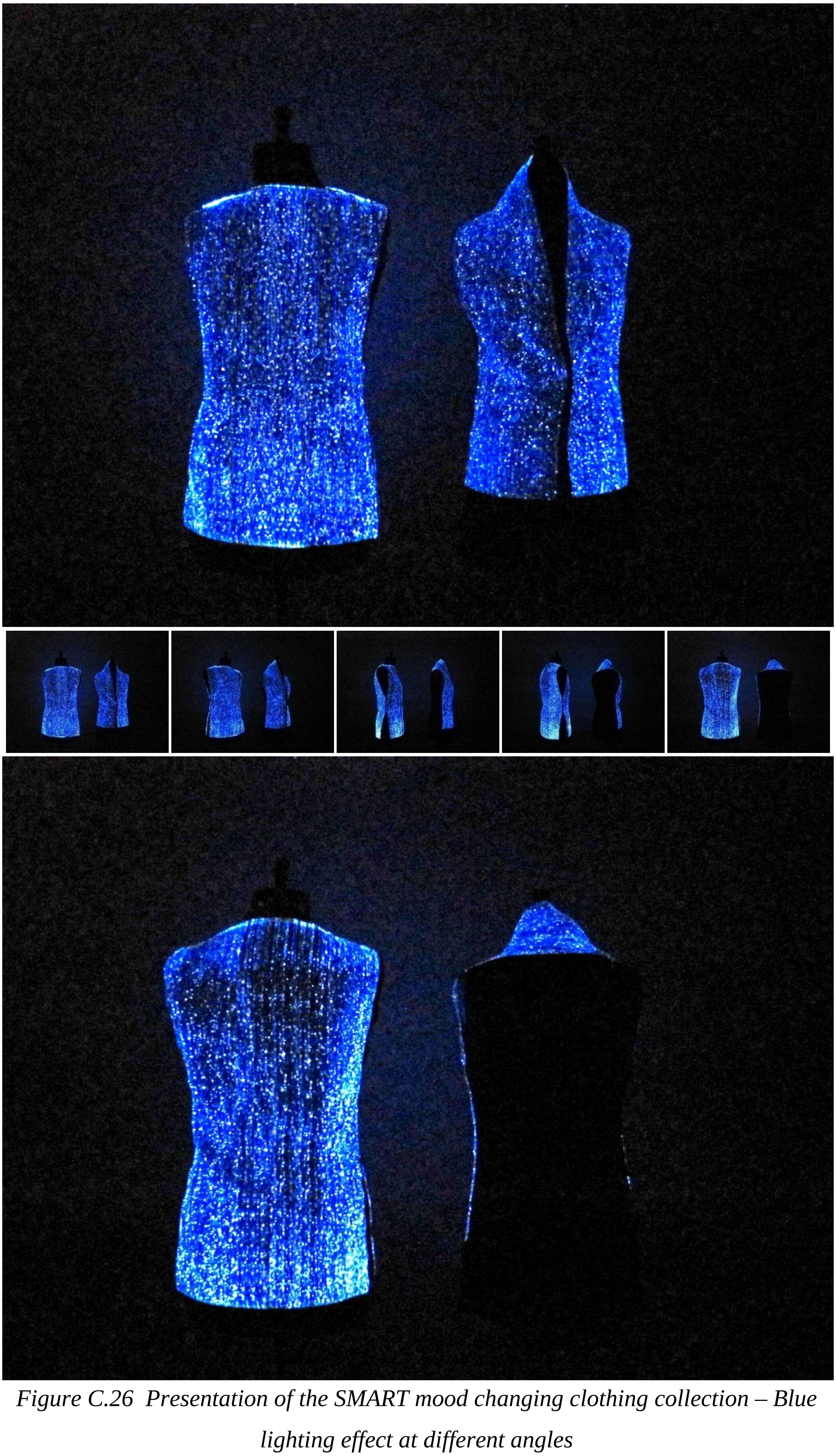


Figure C.26 Presentation of the SMART mood changing clothing collection – Blue lighting effect at different angles